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***Investigation of the tolerance of  
wavelength-routed optical networks to  
traffic load variations***

**Ningning Lao**

A thesis submitted to the University of London for the degree of  
Doctor of Philosophy (Ph.D.)



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*To my parents*

# **Abstract**

This thesis focuses on the performance of circuit-switched wavelength-routed optical network with unpredictable traffic pattern variations. This characteristic of optical networks is termed traffic forecast tolerance.

First, the increasing volume and heterogeneous nature of data and voice traffic is discussed. The challenges in designing robust optical networks to handle unpredictable traffic statistics are described. Other work relating to the same research issues are discussed.

A general methodology to quantify the traffic forecast tolerance of optical networks is presented. A traffic model is proposed to simulate dynamic, non-uniform loads, and used to test wavelength-routed optical networks considering numerous network topologies. The number of wavelengths required and the effect of the routing and wavelength allocation algorithm are investigated. A new method of quantifying the network tolerance is proposed, based on the calculation of the increase in the standard deviation of the blocking probabilities with increasing traffic load non-uniformity. The performance of different networks are calculated and compared.

The relationship between physical features of the network topology and traffic forecast tolerance is investigated. A large number of randomly connected networks with different sizes were assessed. It is shown that the average lightpath length and the number of wavelengths required for full interconnection of the nodes in static operation both exhibit a strong correlation with the network tolerance, regardless of the degree of load non-uniformity.

Finally, the impact of wavelength conversion on network tolerance is investigated. Wavelength conversion significantly increases the robustness of optical networks to unpredictable traffic variations. In particular, two sparse wavelength conversion schemes are compared and discussed: distributed wavelength conversion and localized wavelength conversion. It is found that the distributed wavelength conversion scheme outperforms localized wavelength conversion scheme, both with uniform loading and in terms of the network tolerance.

The results described in this thesis can be used for the analysis and design of reliable WDM optical networks that are robust to future traffic demand variations.

## **Acknowledgements**

**“The grand aim ... is to cover the greatest number of empirical facts by logical deduction from the smallest number of hypotheses or axioms.”**

**Albert Einstein (1879 - 1955)**

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## **Chapter 1 Introduction**

In recent years, the traffic on telecommunications networks increased rapidly. In particular, the boom of the Internet has led to an era of dynamic variability in the world's telecommunication traffic, in contrast to the quasi-static and predictable traffic patterns of previous years. This variability brings great pressure, not only to the high capacity transmission links, but also on core transport networks, specifically, WDM optical networks. It has been observed that both the traffic volumes and the traffic distribution patterns are becoming increasingly unpredictable. Many carefully planned and designed transmission systems and network architectures, based on previously expected traffic scenarios, become inefficient in the adaptation to the new traffic characteristics. Consequently, methods of designing core transport network architectures that have the highest robustness and can accommodate unpredictable traffic variations with minimum blocking probability become an important issue. Moreover, techniques to expand previously deployed network architectures in order to ensure network robustness become very important. In this thesis, the problem of unpredictable traffic distribution patterns in dynamic wavelength-routed optical networks is described and investigated.

The design and planning process of optical networks is a complicated and large scale problem, whereas the research carried out in this PhD work only emphasizes several specific network design issues related to network robustness. In particular, the project set out to answer the questions: how to define the tolerance of optical networks to random traffic pattern variations, what are the factors that influence the network performance under various dynamic traffic loads, and how to improve the network tolerance.

To this end, this thesis concerns three main topics:

- An essential design metric is proposed and investigated in defining and comparing network tolerance to traffic pattern variations
- The sensitivity of network tolerance to physical features of the network topology are investigated
- Methods of improving network performance with variable, non-uniform traffic loads are investigated

The overall objective of this PhD work was to quantify the robustness of dynamic wavelength routed optical networks to traffic variability, to identify the factors that influence this robustness, and hence to improve the performance of wavelength routed optical networks.

## Overview of the thesis

The basic background and development of optical networks is described in Chapter 2. Firstly, the wavelength division multiplexing (WDM) concept, WDM transmission systems, and WDM networks with related network element technologies are described. Optical network architectures, optical switching technologies, and traffic evolution in optical networks are discussed. Finally, the challenges from rapidly varying dynamic traffic loads are described and discussed in detail. The uncertainties of future traffic dynamics, both from the point of view of the traffic volume and the traffic patterns, bring significant challenges to wavelength-routed optical network architecture design, planning, and expansion. As it is very hard to estimate where and when “hot-spots” might appear in the network, it is very difficult to design and expand a network that can generally satisfy any future network needs under all possible conditions. Thus a network design technique is needed to carefully assess and compare the robustness of any network to accommodate the unpredictable traffic dynamics. While, many studies have been carried out in network design, tackling problems of increasing traffic volume, the impact of traffic pattern variations are usually neglected. The aim of this work was to develop techniques or methodologies for designing and expanding dynamic wavelength-routed optical networks in ways that maximise the network’s ability to handle future unpredictable traffic pattern fluctuations.

In chapter 3, a detailed investigation of dynamic wavelength-routed networks’ capability to carry unexpected traffic pattern variations, termed traffic forecast tolerance, is carried out. Firstly, a novel traffic model to simulate the traffic pattern variations is proposed. In addition, a technique based on the traffic model to test the network performance with different traffic scenarios is described and discussed. Moreover, the technique is further employed and tested with various routing and wavelength allocation algorithms ranging from “best” to “worst” algorithms, with a large number of network topologies, ranging from deployed networks, such as NSFNET, to randomly connected networks, and with traffic scenarios ranging from uniform to highly non-uniform. Secondly, a method of quantifying the traffic forecast tolerance is presented, allowing different network designs to be compared in terms of

their ability to handle unpredictable traffic variations. Thirdly, the technique is integrated in a mathematical model to calculate the traffic forecast tolerance analytically. The results from mathematical model are directly used to validate the simulation results.

In chapter 4, a detailed investigation of the sensitivity of traffic forecast tolerance to the physical features of the network topology is carried out, through both theory and simulations. In particular, the average lightpath length and the wavelength requirement to fully interconnect all network nodes in static operation are studied. The results generated from this chapter can be used as a general guidance to design and extend dynamic wavelength-routed optical networks.

An investigation of the effects of wavelength conversion on the network traffic forecast tolerance is carried out in Chapter 5. Firstly, the wavelength conversion schemes, optimal wavelength conversion placement, and RWA algorithms with wavelength conversion facilities are discussed in detail. Secondly, a novel dynamic operating scheme in optical networks with wavelength conversion facility is proposed and further utilised in the following studies. The benefits of wavelength conversion on the traffic forecast tolerance is assessed. This is followed by comparison of two sparse wavelength conversion schemes, namely localised and distributed schemes, in terms of their effect on the network traffic forecast tolerance.

Finally, chapter 6 provides a summary of the work carried out during the course of this research. In addition, possible areas for further research are identified.

## Original contributions

The original contributions to the field of dynamic wavelength-routed optical networks resulting from this PhD project are summarized below:

- Proposed a novel traffic model that can simulate dynamic traffic pattern variations [Lao03c] [Lao04b] [Lao05a]
- Proposed a novel metric to define and measure the robustness of dynamic wavelength routed optical networks with unpredictable traffic pattern variations [Lao04b]
- Developed a novel technique based on the proposed traffic model to quantify the robustness of dynamic wavelength-routed optical networks to accommodate the dynamic traffic pattern fluctuations, termed network traffic forecast tolerance [Lao03c] [Lao04b] [Lao05a]
- Integrated the proposed technique into an analytical model and further extended the model to calculate and validate the network traffic forecast tolerance theoretically
- A first study of dynamic wavelength-routed optical network design using static network design technique was carried out. The wavelength requirement for static operation was shown to correlate with traffic forecast tolerance [Lao04b] [Lao05b] [Lao05a]
- An investigation of the effect of network physical topological features on traffic forecast tolerance was carried out. The sensitivity of the traffic forecast tolerance to the average lightpath length was studied [Lao03b] [Lao03a] [Lao04b] [Lao05b] [Lao05a]
- Proposed a novel network operating scheme with wavelength conversion facility based on fixed alternate routing and first-fit wavelength allocation algorithm in order to efficiently utilise wavelength conversion resources
- A first assessment of the effects of wavelength conversion on traffic forecast tolerance was carried out [Lao04b]
- Compared two sparse wavelength conversion schemes in the context of traffic forecast tolerance. The distributed placement scheme was shown to outperform the localized placement scheme [Lao04a] [Lao05a]

## List of refereed journals and conferences

The following is a list of publications that arose as a result of the research described in this thesis. The list is given in descending chronological order.

- [Lao05a] **Roger N. Lao**, Robert Friskney, Robert I. Killey, "Investigation of the tolerance of wavelength-routed optical networks to inaccuracy in traffic-load forecasts," Optical Society of America (OSA), Journal of Optical Networking, Vol. 4, No. 3, pp. 144 - 156, March 2005. <http://www.osa-jon.org/abstract.cfm?URI=JON-4-3-144>
- [Lao05b] **Roger N. Lao**, Robert Friskney, Robert I. Killey, "Investigation of the tolerance of wavelength-routed optical networks to inaccuracy in traffic load forecasts," IEEE/OSA Optical Fiber Communication Conference (OFC/NFOEC2005), Proc. paper OThS4, Anaheim, California, USA, 6-11 March, 2005.
- [Lao04a] **Roger N. Lao**, Robert Friskney, Robert I. Killey, "Effect of sparse wavelength-conversion on network tolerance to inaccuracy in traffic load forecasts," 30<sup>th</sup> European Conference on Optical Communication (ECOC2004), Proc. Vol. 2, pp. 170 - 171, paper Tu1.6.3, Stockholm, Sweden, 5-9 September, 2004.
- [Lao04b] **Roger N. Lao**, Robert I. Killey, "Wavelength-routed optical network tolerance to inaccuracy in traffic load forecasts," IEEE/OSA Optical Fiber Communication Conference (OFC2004), Proc. paper ThG4, Los Angeles, California, USA, 22-27 February, 2004.
- [Lao03a] **Roger N. Lao**, Robert I. Killey, "Impact of wavelength-routed network physical topology on blocking probability using a dynamic traffic growth model," Optoelectronics and Communication Conference (OECC2003), Proc. Vol. 2, pp. 773 - 774, Shanghai, China, 13-16 October, 2003.



- [Lao03b] **Roger N. Lao**, Robert I. Killey, “Design of wavelength-routed optical network topologies to minimise lightpath blocking probabilities,” London Communication Symposium (LCS2003), Proc. Vol. 1, pp. 305 - 308, University College London, London, UK, 8-9 September, 2003.
- [Lao03c] **Roger N. Lao**, Robert I. Killey, “An investigation of wavelength-routed optical network performance using a traffic growth model,” EPSRC Postgraduate Research Conference in Electronics, Photonics, Communications and Networks, and Computing Science (PREP2003), Proc. Vol. 2, pp. 101 - 102, University of Exeter, Exeter, UK, 14-16 April, 2003.

## **Chapter 2 Background and Literature Review**

### **2.1 Overview of optical network development**

Optical communication techniques and optical networks have experienced rapid changes from the early 1970s, driven by the ever-increasing demand of global information communication. In the 1990s, the technique of wavelength division multiplexing (WDM) was introduced commercially, exploiting the enormous optical bandwidth of each fibre. The development of new techniques in optical fibre types, signal amplification, optical signal regeneration, and optical switches, has allowed the transmission of information over increasing distances with higher capacities. In the current decade, point-to-point fibre transmission systems based on WDM have gradually evolved to WDM-based optical networks. The technique of WDM has been upgraded from the simple physical media layer to the optical path layer, where it eliminates the requirements of electronic-optical conversion and buffering at the intermediate nodes. In addition, WDM-based optical ring and mesh networks have started to appear with the development of optical cross-connects (OXC) and optical add-drop multiplexers (OADM). In the foreseeable future, optical networks with high intelligence can be expected, in which network management, network reconfigurability, and network restoration can be realised directly in the optical layers. In such networks, wavelengths could be dynamically set up and torn down according to dynamic traffic requests.

The popularity of data communications, especially the growth of the Internet, is another main driver behind the development of optical networks and related techniques. The exponential increase of data traffic has already taken the lead over the steadily increasing voice traffic at the end of 1999 [Muk00]. Data traffic is predicted to dominate the networks very soon. The need for high bandwidth in the Internet and the promise of WDM to provide this high capacity are pushing the development of IP-over-WDM. In the near future, both voice and data traffic could be directly transformed into IP (Internet Protocol) packets and transmitted over WDM optical

networks with a high level of intelligence. Moreover, the trend is leading to all-optical networks (AON).

## **2.2 Key optical technologies and systems**

In this section the technologies and systems that are relevant to optical networking are introduced.

### **2.2.1 Wavelength division multiplexing and WDM networks**

#### **2.2.1.1 Introduction of wavelength division multiplexing techniques**

Silica fibre has an extremely high bandwidth, approximately 25 THz. However, only tens of gigabits per second can be achieved by each transceiver, as the electronic speed limits the access to the huge bandwidth offered by fibres. Hence it is very difficult to exploit the huge bandwidth of a single fibre using a single high-capacity wavelength channel, due to the mismatch between optical and electronic bandwidths. Wavelength division multiplexing is a promising method of sending many light beams each at different wavelengths simultaneously down the core of an optical fibre.

Theoretically, WDM is similar to frequency division multiplexing (FDM). In WDM, multiple signals, each generated by a pair of transmitters, are modulated onto a carrier at different optical frequencies (wavelengths). The combined wavelengths are then transmitted simultaneously over one single optical fibre. An example of wavelength division multiplexing is shown in Fig.2.1.

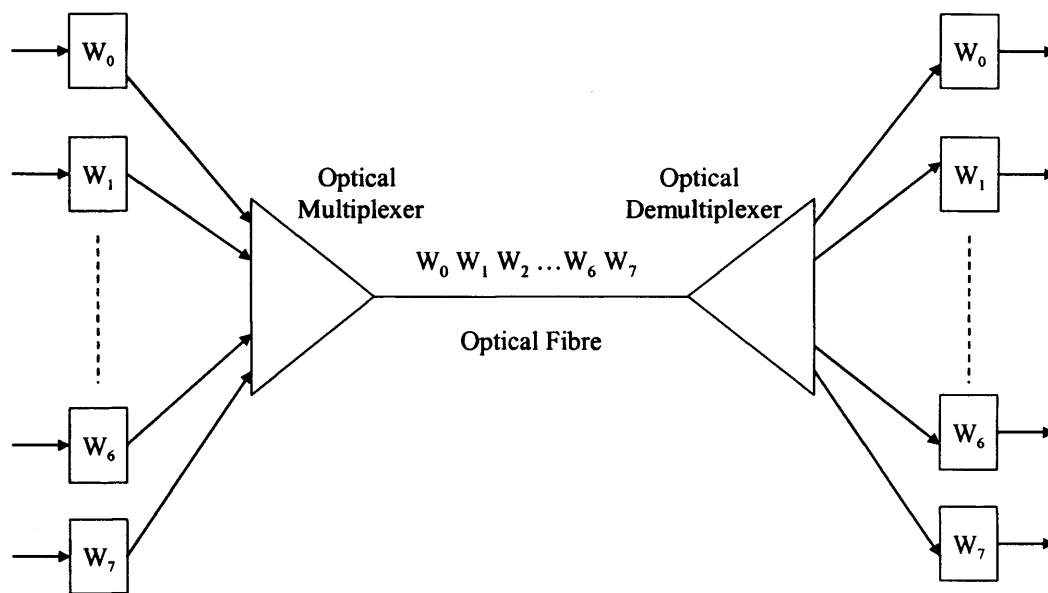


Figure 2.1 - Wavelength division multiplexing (WDM) technique

WDM point-to-point links have been deployed to accommodate increasing bandwidth demands between transmission nodes. This was the earliest application of WDM technology, which multiplies the capacity of a single fibre link by the factor of the number of wavelengths that are transmitted over the fibre link. A schematic of a WDM point-to-point link is shown in Fig.2.2.

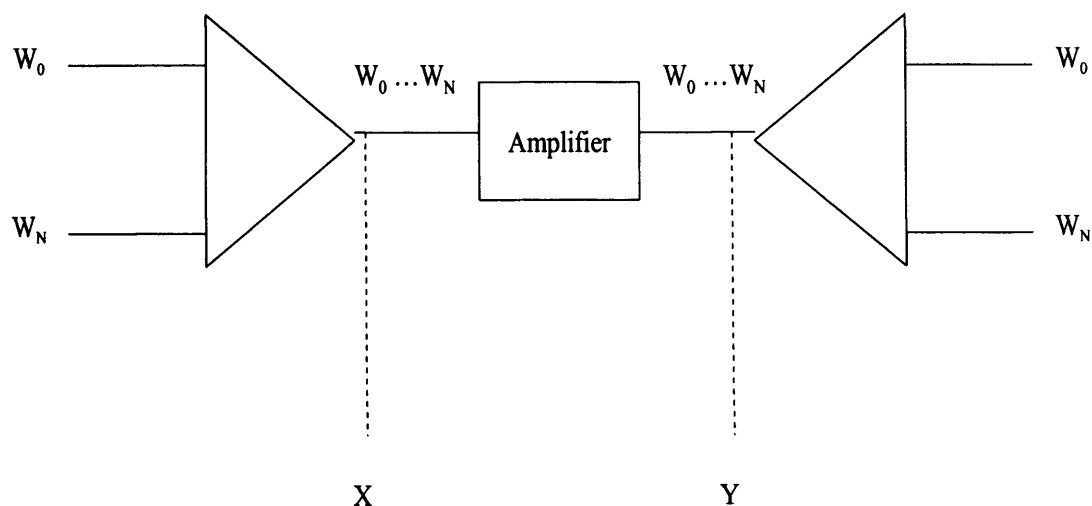


Figure 2.2 - WDM point-to-point link

### 2.2.1.2 WDM network architectures

There are two main classes of WDM optical network architectures: broadcast-and-select networks and wavelength-routed networks.

A broadcast-and-select network has a passive star coupler connecting the nodes in the network, as shown in Fig.2.3. Each node is normally equipped with an optical transmitter and an optical receiver. Different nodes transmit messages at the same time on different wavelengths, and the passive optical coupler is used as a combiner and splitter. Thus, transmission from each node is broadcast to all the others. At each node, the desired optical signal is filtered out from the entire WDM spectrum by a tuneable filter in the receiver.

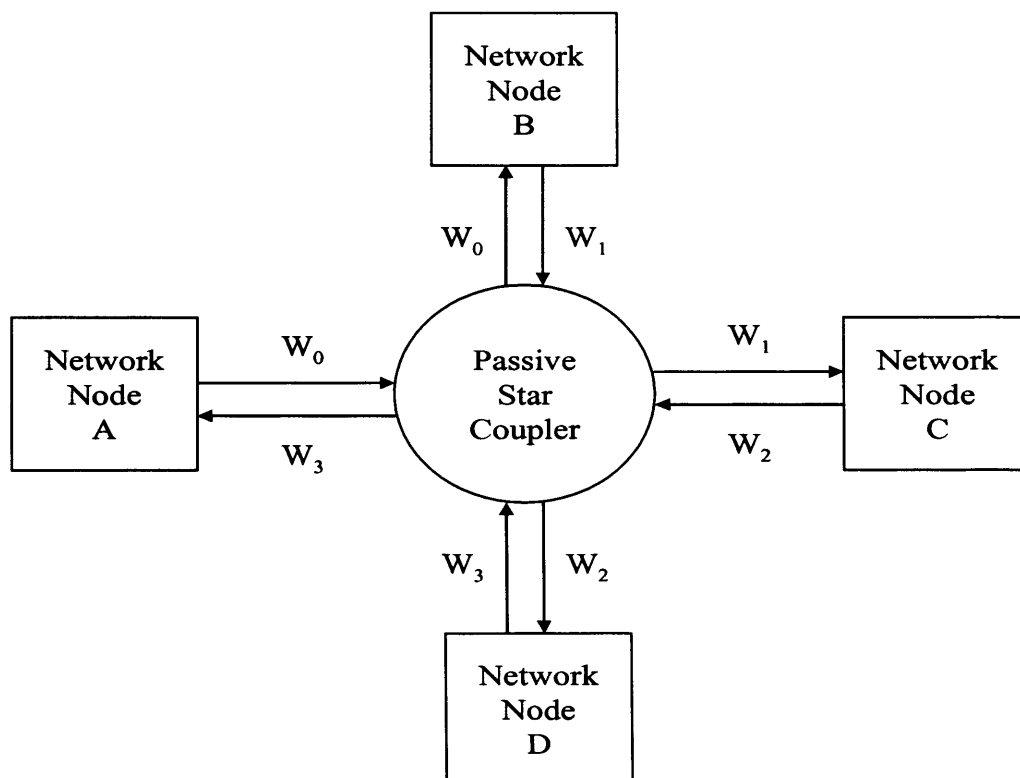


Figure 2.3 - Broadcast-and-select network physical topology

A broadcast-and-select network is simple to implement. However, it has severe limitations. Since the optical signals share the fibre infrastructure in the network, the number of distinct wavelength required is at least as many as the number of active nodes in the network. Moreover, the physical size of the network is constrained due to

the inherent power split by the passive star coupler, since the transmitted power is shared among all the nodes, so that each node only receives a small fraction of the power. It becomes worse with the increase in the number of wavelengths required. Therefore, the broadcast-and-select network is only likely to be implemented in areas such as local and metropolitan environments.

In the case of wide area transport networks, where network nodes tend to be arbitrarily connected by optical fibre links, wavelength routing is often used to achieve better performance. In wavelength-routed optical networks (WRONs), high-capacity optical signals are routed according to their wavelengths. The wavelength routing is achieved through photonic switching fabrics based on optical switches, with or without wavelength conversion, or using electronic switching. Each end-user is connected to an optical switch via a fibre link. The end-user and the corresponding switch are referred together as a network node. Fig.2.4 shows a schematic of a wavelength-routed optical WDM network.

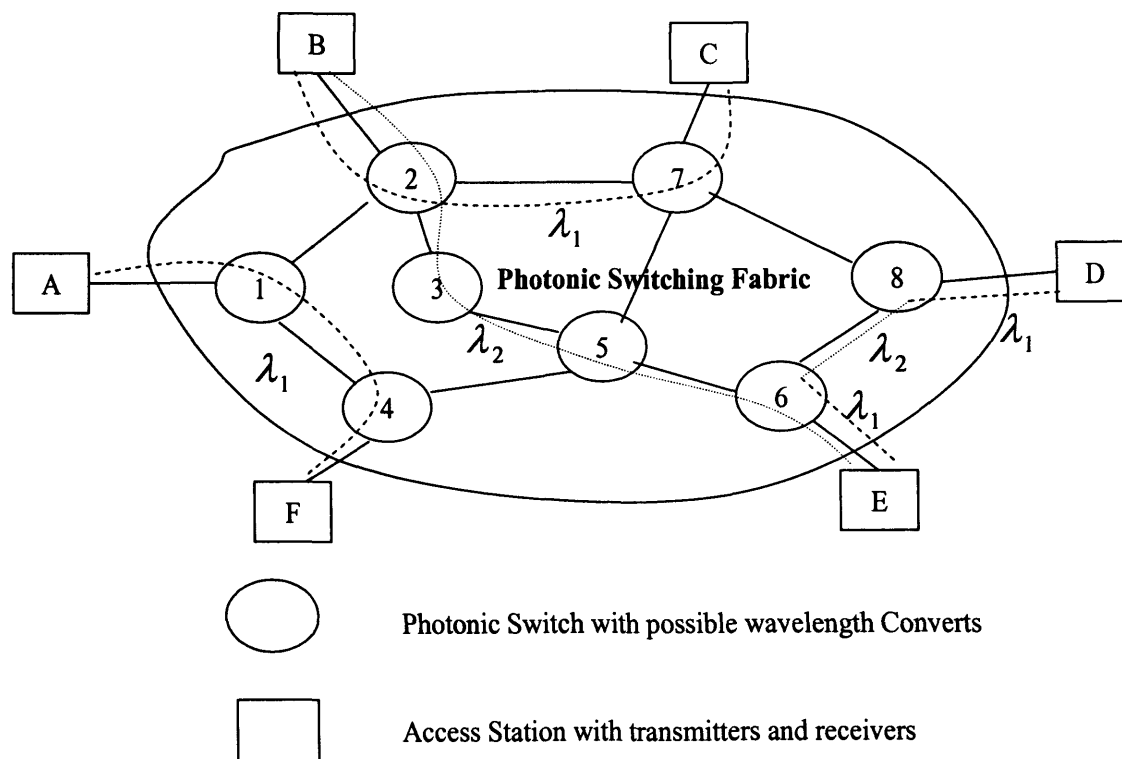


Figure 2.4 – A schematic of a wavelength-routed WDM-based optical network

The basic communication in a wavelength-routed network is termed a lightpath. In an all-optical WRON, a lightpath is an optical communication channel between any two nodes in the network, and it may span more than one fibre link. The intermediate nodes in the fibre path route switch the lightpath using optical switches. The end-users access the lightpath with transceivers tuned to the wavelength on which the lightpath travels. With the absence of wavelength conversion facilities, a lightpath travels on the same wavelength over the whole path route. This is often referred to as the wavelength-continuity constraint. Hence, in wavelength-routed networks, two or more lightpaths traversing the same fibre link must be on different wavelengths in order not to interfere with each other.

### 2.2.2 Long haul and ultra long haul transmission

The transmission distance for a WDM link over a few hundred kilometres is often regarded as long haul (LH) transmission, whereas ultra long haul (ULH) transmission is over several thousand kilometres. Long-haul systems typically achieve a reach of 600 km before requiring regeneration. Ultra-long haul systems achieve a reach of over 2000 km. Metro systems are designed to provide lower-cost bandwidth over shorter distances, up to about 100 km [Ram02]. With the development of erbium-doped fibre amplifier (EDFA), new modulation schemes, and new fibre types, the transmission capacity and transmission distance are being improved upon constantly. Fig.2.5 shows transmission capacity development with a time frame [Ram02]. Fig.2.6 shows the transmission distance with corresponding capacity in Terabits/s [Zhu04]. The channel rate has been increased from 2.5Gbit/s in the mid-1990s to currently 40Gbits/s. The latest result is a capacity up to 6.4 Terabits/s per fibre over 3200 km, which was reported in [Zhu03]. This is achieved through 40 Gb/s per channel and 160 channels using  $32 \times 100$  km fibre spans.

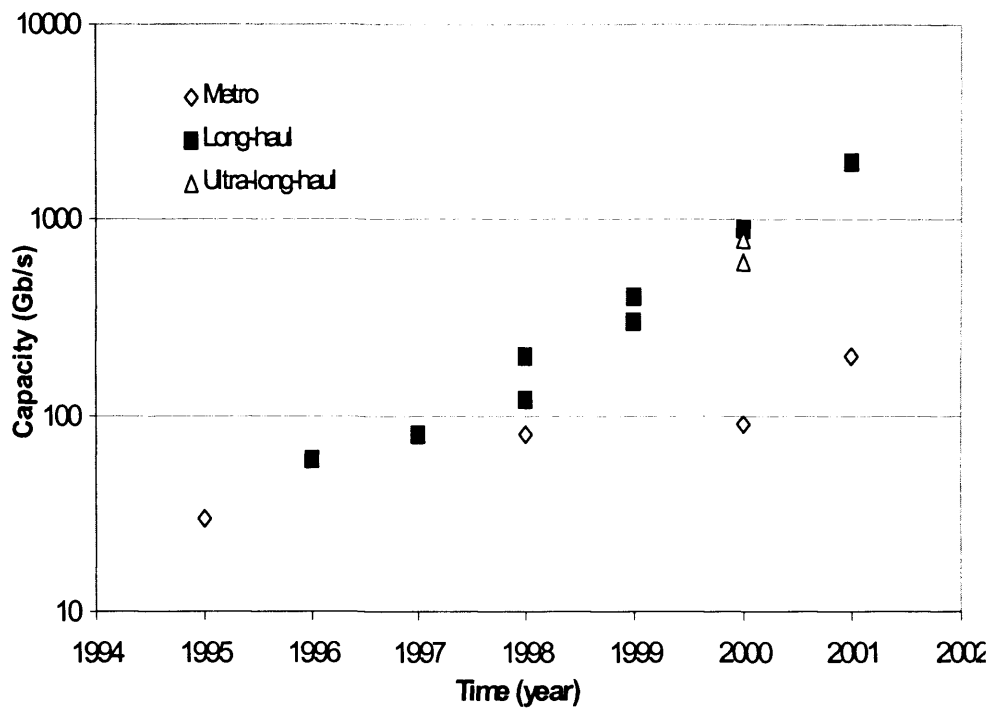


Figure 2.5 – Transmission capacity of commercially available WDM systems [Ram02]

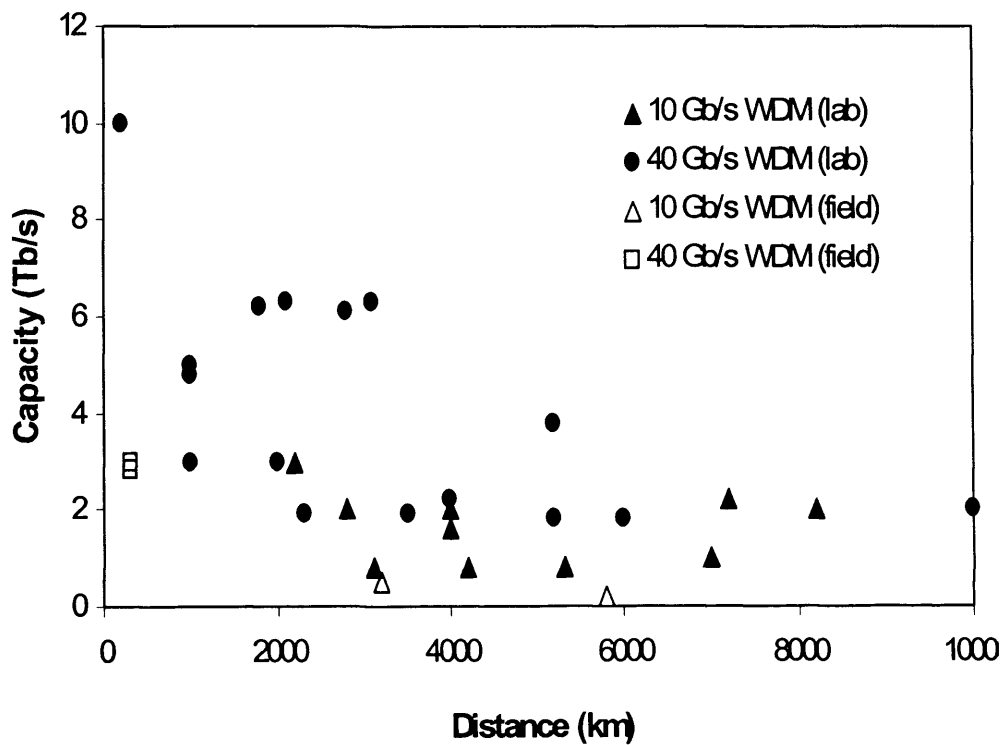


Figure 2.6 – Major results of 10 Gb/s and 40 Gb/s DWDM transmission achievements [Zhu04]



### 2.2.3 Network Elements

An introduction of the network elements is presented. These network elements are used as the basic building blocks for the optical network architecture, which is investigated throughout the thesis.

#### 2.2.3.1 Optical fibre

Single mode optical fibres are commonly used in most modern WDM transmission systems to overcome the distance limitations introduced by intermodal dispersion in multimode propagation [Ram98]. In single-mode fibre, light travels in a straight line along the centre axis of the fibre. There are two transmission windows (referred to as bands) which have low attenuation for an optical fibre to transmit signals, at wavelengths around 1310 nm and 1550 nm [Muk00]. Categorized bands and sub-bands can be found in [Zhu04].

There are many different types of fibre, which offer different characteristics to maximise transmission capacity and distance in WDM links. A description of the various fibre types can be found in [Ram98], with a review of the major transmission impairments such as attenuation, chromatic dispersion, and fibre non-linearity. Three types of the most commonly deployed fibres in long haul networks are described as follows.

Standard single-mode fibre has zero chromatic dispersion at  $\lambda = 1310$  nm, which is suitable for short distance transmission or single channel operation. However, the dispersion at the minimum loss wavelengths around  $\lambda = 1550$  nm (the wavelength at which the commonly-used erbium-doped fibre amplifier (EDFA) operates) at which dense wavelength division multiplexing (DWDM) operates is high, so that dispersion compensation is needed.

Dispersion shifted fibre has zero dispersion at 1550 nm. However, inter-channel nonlinear effects, such as four-wave mixing, appear at low dispersion level.

Nonzero dispersion fibre has a low level of dispersion in the 1550 nm band and low nonlinear effects. However, this kind of fibre is relatively expensive, although is ideal for DWDM applications.

Fibres are usually deployed in a way that bi-directional transmission could be either realized on a single fibre using filters and circulators to separate the two signal directions, or using two distinct fibres for each direction of transmission.

### 2.2.3.2 Transmitters

Lasers are used as optical sources to transmit optical signals over the fibre. The lasers are stimulated by electronic current and emit intense high-powered beams of coherent light, which contains one or more distinct frequencies.

Lasers are categorized as tunable and fixed wavelength. In WDM networks the tunable lasers are starting to become popular, as they simplify inventories of replacement parts, and as the transmitters are required to tune to different wavelength in short periods of time. The primary characteristics for a tunable laser are the tuning range and the tuning time. The tuning range is the wavelength range over which the laser can operate. The tuning time is the time period for the laser to tune from one wavelength to another.

There are mechanically tuned lasers, acoustooptically and electrooptically tuned lasers, and injection-current-tuned lasers. These lasers work using different mechanisms, and hence each has a different tuning time and tuning range. Tab.2.1 shows the optical tunable transmitters and their associated tuning ranges and times [Muk97].

Tunable Transmitter	Approx. Tuning Range (nm)	Tuning Time
Mechanical (external cavity)	500	1 – 10 ms
Acoustooptic	83	~ 10 $\mu$ s
Electrooptic	7	1 – 10 ns
Injection – Current (DFB and DBR)	10	1 – 10 ns

Table 2.1 - Tunable optical transmitters with associated tuning ranges and times  
[Muk97]

### 2.2.3.3 Receivers

The major characteristics for optical receivers are detector efficiency, the operating wavelength, and the response time. The detector efficiency is the ratio of output electrical power to the input optical power. Obviously, an ideal optical receiver has high detector efficiency. The operating wavelength is the range over which the receiver has a response. The response time refers to how quickly the receiver reacts to variations in the light intensity.

Among the most commonly used optical detectors are PIN diodes and Avalanche Photodiodes (APDs). PIN diodes detect photons at energies higher than the bandgap energy. APDs not only detect the photons, but also amplify the signals. A good description of the above optical receivers could be found in [Gor01].

### 2.2.3.4 Amplifiers

Amplification in the optical transmission is necessary, as optical signals attenuate after propagating over a certain distance (by approximately 0.2 dB/km in standard single-mode fibre). There are three forms of amplifications. 1R regeneration refers to signal power amplification only. It boosts the power of the signal, without restoring the shape or timing of the signal, and offers the lowest cost for future WDM optical networks, and greatest convenience, since 1R provides signal format and bit-rate transparency. Other forms are 2R regeneration, which includes both amplification and reshaping, and 3R amplification, which provides regeneration, reshaping, and reclocking. Reshaping reproduces the original signal pulse shape, whereas reclocking synchronizes the signal to its original timing. Both reshaping and reclocking require the conversion the optical signals back to the electronic domain and further conversion for the reshaped and reclocked electronic signals back to the optical domain. This optical-electronic-optical process slows the transmission process and comes at a high cost due to the requirement for additional lasers and detectors. Although 2R and 3R regeneration offer better performance than 1R regeneration, they have a lack of optical transparency, which is less preferable for the future all-optical networks.

There are two basic types of optical amplifiers. They are semiconductor laser amplifiers and rare-earth-doped-fibre amplifiers. The most common element with which the fibre is doped is erbium (a rare earth). The erbium-doped-fibre amplifier (EDFA) provides gain for wavelengths between 1525 nm and 1560 nm. The main characteristics of amplifiers are gain, gain bandwidth, and working range. Gain measures the ratio of the output to input powers. The gain bandwidth is the amplifier's effective signal wavelength range. Working range is the wavelength range over which the amplifier operates. Tab.2.2 shows a brief comparison between semiconductor based amplifier and rare earth based amplifiers given in [Muk97].

<i>Amplifier Type</i>	<i>Gain Region</i>	<i>Gain Bandwidth</i>	<i>Gain</i>
Semiconductor	Any	40 nm	25 dB
EDFA	1525 – 1560 nm	35 nm	25 – 51 dB
PDFFA	1280 – 1330 nm	50 nm	20 – 40 dB

Table 2.2 - Amplifier characteristics [Muk97]

### 2.2.3.5 Wavelength conversion

Wavelength conversion is sometimes referred to as wavelength translation. Wavelength conversion will break the wavelength-continuity constraint, as it allows signals entering a network node on one wavelength to switch to another wavelength on the output fibre. This brings the great convenience to the wavelength-routed optical network that a lightpath may not be required to use the same wavelength throughout the fibre-link-composed physical path. This potentially eases the problem of wavelength contention and reduces the request blocking probability. However, wavelength conversion comes at a high cost.

Wavelength conversion technologies fall into two main types, opto-electronic wavelength conversion and all-optical wavelength conversion. Opto-electronic wavelength conversion requires the optical signal to be converted into the electronic domain, whereas with all-optical wavelength conversion, the signal remains in optical form. All-optical wavelength conversion can be further divided into coherent effect-based wavelength conversion and cross modulation wavelength conversion. Among

the different technologies, all-optical wavelength conversion is much preferred, as it provides the signal transparency. In particular, wave-mixing conversion technology offers a full range of transparency while allowing simultaneous conversion of a batch of wavelengths. Further description of wavelength conversion technology can be found in [Myn01].

### 2.2.3.6 Optical add-drop multiplexers (OADMs)

An optical add-drop multiplexer is a device that can add or drop a wavelength to the main data streams. In wavelength-routed optical networks, in which wavelengths are routed among network nodes, a portion of the wavelengths are terminated at each network nodes, where they have reached their destination. Hence OADM's are used to direct the wavelengths that are terminated and dropped locally. At the same time, new wavelengths originating from each network node are required to be inserted into the main data streams, and the OADM's are used to carry out this operation. OADM's are very important building blocks for the optical networks, as they increase the flexibility of WDM implementations. Fig.2.7 shows an example of an OADM.

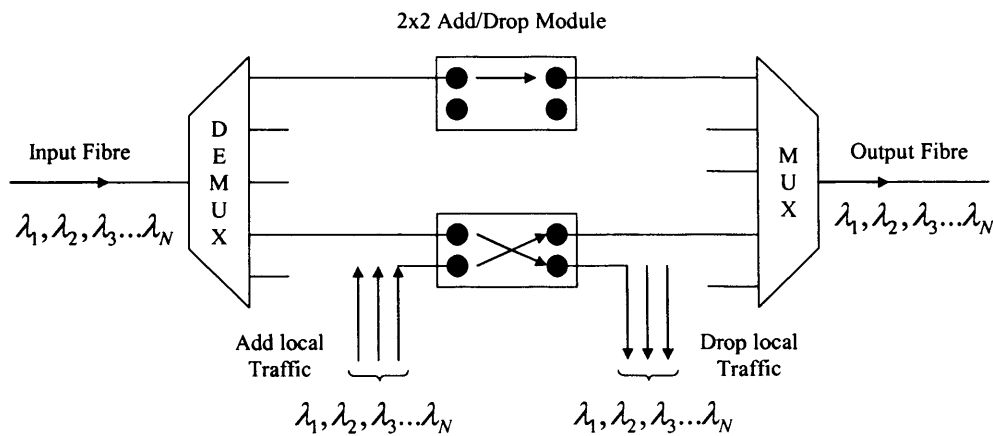
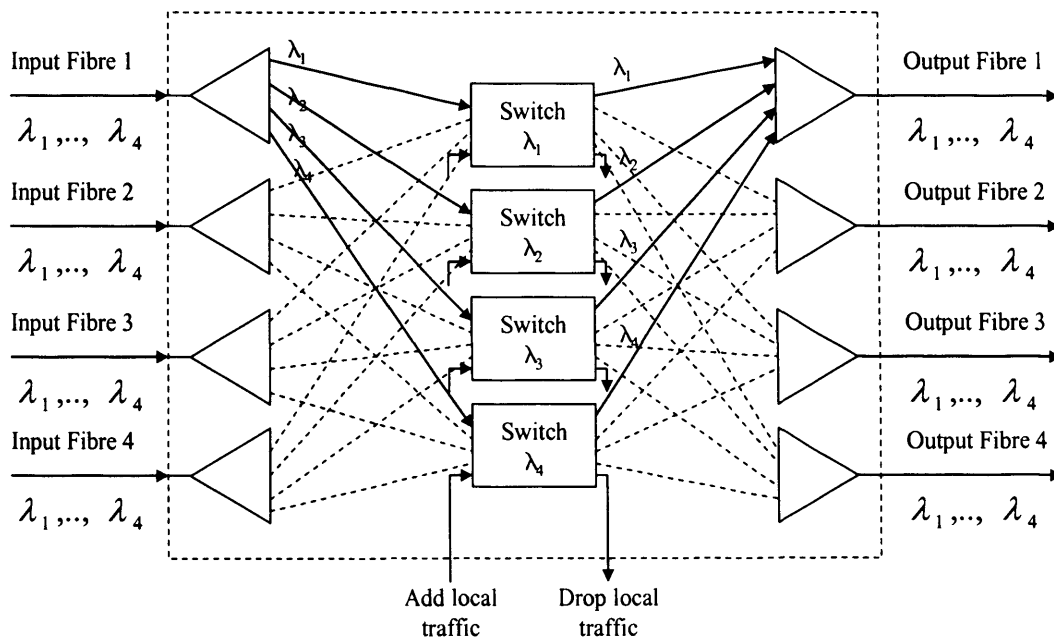


Figure 2.7 - An example of optical add/drop multiplexer

### 2.2.3.7 Optical cross-connects (OXC)

An even more flexible WDM multipoint network can be realized using optical cross-connects, which can switch any input wavelength from an input fibre to any output fibre on any wavelength in the optical domain. There are two main types of OXCs. They are active OXCs and passive OXCs. The wavelength on a given input port gets routed to an output port depending on the internal connections between demux and mux devices inside the switch. The passive OXCs can separately route each of several wavelengths on an input fibre to the same wavelength on separate output fibres, whereas an active OXC allows reuse of the wavelengths. It not only supports simultaneous connections, but can also be reconfigured on demand to change the internal connections between mux and demux.

(a)



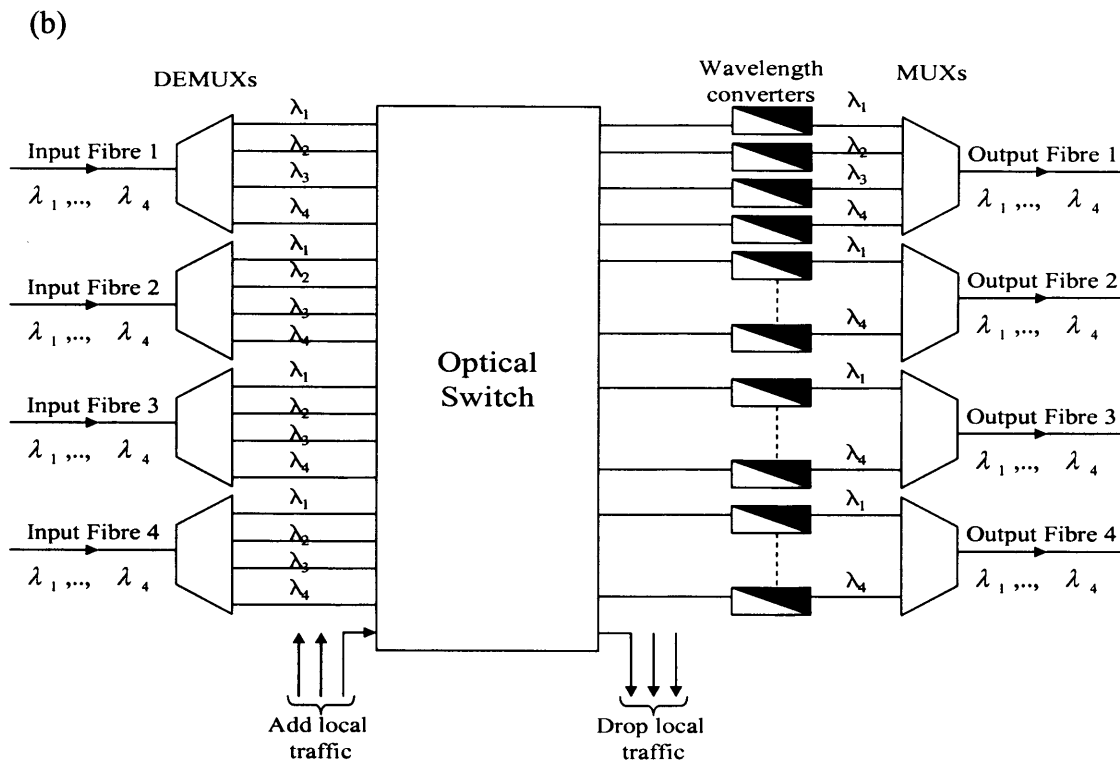


Figure 2.8 – (a) A 4 x 4 active optical cross-connect without wavelength conversion (four wavelengths) (b) A 4 x 4 active optical cross-connect with wavelength conversion (four wavelengths)

Moreover, additional capability of wavelength conversion can be integrated into the OXCs. Fig.2.8 (a) and (b) show examples of OXC without and with wavelength conversion facility respectively.

## 2.3 Network architecture

The combination of optical technologies and individual network elements discussed in the previous sections forms the basic optical networking architecture. In this section, the hierarchy of the telecommunication networks are first presented in terms of physical size and functionality. Following this, the different layers of the networks are explained. The section concludes with a description of future optical network architecture evolution.

### 2.3.1 Network hierarchy

Network hierarchy is presented in terms of physical size and functionality. The network hierarchy could also be classified based on the line rate [Myn01].

#### 2.3.1.1 Access network

Access networks are sometimes referred to residential area networks. End-users' traffic, which includes voice traffic, Internet traffic (IP traffic), and other types of traffic, is aggregated at the local exchanges. There are many options to realise the transmission between the end-users and the local exchanges, from copper wires to fibre to the home (FTTH) technology. FTTH is only deployed in a few countries, including Japan and Korea. For most other countries, FTTH has proved difficult to implement. As conventional telephone wires are already deployed, duplicate investment is always an issue. This is often described as the "last mile" problem. The access network usually carries a line rate of 155 Mbit/s to 622 Mbit/s.

#### 2.3.1.2 Metro network

In metropolitan areas, the access network traffic is groomed and interconnected. End-users that require high speed data connections have appeared, which include enterprises, hospitals, and universities. Optical networking technologies have been implemented in the metro area network including synchronous digital hierarchy (SDH) and simple WDM systems. The metro network carries up to 2.5 Gbit/s.

#### 2.3.1.3 Core network

The core network usually refers to the backbone transport networks, which connects the major cities and continents over long distances.



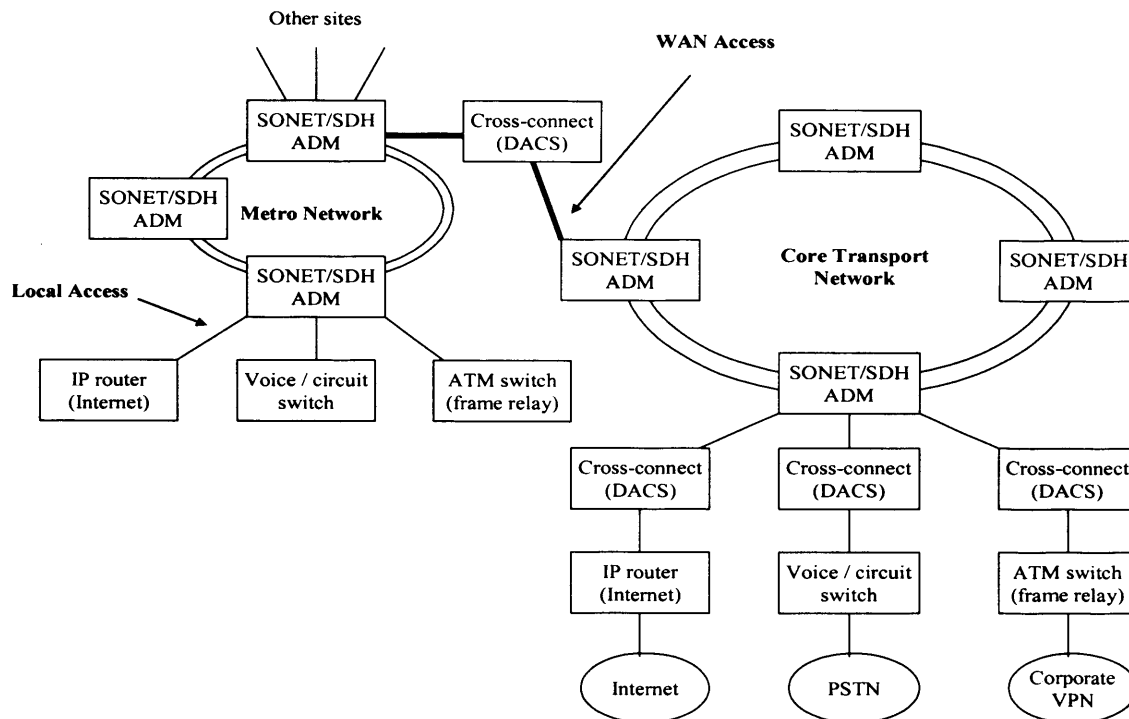


Figure 2.9 - Network hierarchy descriptions [Gor01]

Transport networks are built based on the WDM transmission systems. Different service layers are provided on top of each other, which might include the IP, asynchronous transfer mode (ATM), and SDH or its American counterpart SONET.

Fig.2.9 shows a generic description of interconnection between access network, metro network, and core network [Gor01]. The core network carries from 2.5 Gbit/s to 10 Gbit/s per wavelength.

### 2.3.2 Network layers

Networks are usually explained using a layered approach, referring to as the open systems interconnection (OSI) model. This section introduces optical networks in terms of different layers.

### 2.3.2.1 Optical layer

The optical layer provides lightpaths to the higher layers. The Telecommunication Standardization Sector for the International Telecommunication Union (ITU-T) has introduced and defined a new layer: the Optical layer [ITU01]. There are three sub-layers in the optical layer as shown in Fig.2.10.

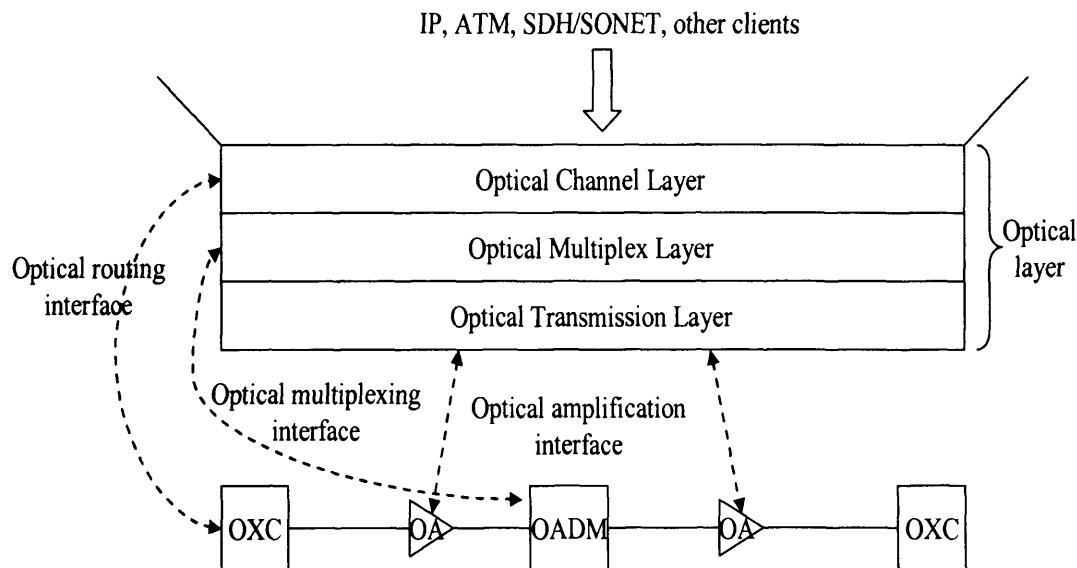


Figure 2.10 - Optical layer structure with corresponding functionality

The bottom sub-layer is called the optical transmission layer, which provides amplification functions to the layers above. The middle layer is the optical multiplex layer, which represents the point-to-point connection between WDM nodes along the entire route of a lightpath. The top layer is responsible for the lightpath routing across the whole network. WDM point-to-point links are connected with SDH/SONET elements. They are logically defined as the optical layer, which transport the SDH/SONET frames without affecting SDH/SONET overheads.

### 2.3.2.2 Optical layer transparency

Transparency in optical networks means that a lightpath supporting data transmission is independent of the data bit rates, data format, and the underlying protocols. It also means that there is no need for electronic processing, in particular, the O-E-O conversion over the entire transmission path from source to destination.

As mentioned in the previous section, a transparent all-optical network is a network in which no electronic signal regeneration is performed throughout the whole network. On the contrary, if regeneration is performed at all the network nodes, the network is said to be opaque or partially transparent. In the opaque optical network, the transparency is limited to point-to-point hops between neighbouring network nodes. The point-to-point optical signal transmission system may be equipped with optical amplification.

Due to the current physical limitations on optical transparency, many hybrid solutions have been proposed to combine both transparent and opaque optical networking. These solutions include transparent sub-networks and islands of transparency, which are small optical transparent domains existing within a larger network [Gre01]. At the boundaries of small optical transparent domains, 3R regeneration is performed. All lightpaths crossing the boundaries will undergo the regeneration process.

### 2.3.2.3 SDH/SONET layer

An SDH/SONET network relies on optical fibre as its transmission media; however most of the SDH/SONET equipment is still electronic. This is the reason why SDH/SONET is sometimes referred as the first generation of fibre optic networks. An SDH/SONET transmission system might include fibres, terminal multiplexers, regenerators, add/drop multiplexers, and digital cross-connects. SDH/SONET employs the time division multiplexing (TDM) technique. It provides an efficient and reliable way to aggregate and manage the traffic from the above layers. The SDH/SONET system is a single wavelength optical networking standard that provides protection and restoration to ensure the survivability through the functions of different sub-layers.

The SDH/SONET layer consists of several sub-layers, which include the path layer, line layer, section layer, and physical layer. Similarly to the optical layer, each sub-layer in the SDH/SONET layer has a different function. The path layer is responsible for the transmission of bits over physical media. The section layer is responsible for error monitoring and control with signal regeneration. The line layer is responsible for multiplexing top layer connections. It also provides the administration, management,

and operating functions. The path layer monitors and tracks the status of the connections. A detailed description of SDH/SONET can be found in [Gor01].

#### **2.3.2.4 ATM layer**

An ATM network can be accomplished with any physical network, such as SDH/SONET. An ATM network is connected by ATM switches. Data cells are routed and transmitted across the ATM network. ATM is carried frequently using SDH/SONET framing.

Similarly to the optical layer and SDH/SONET layers, the ATM layer has several sub-layers, which include the physical layer, ATM layer, and adaptation layer. Each has its own function. A detailed description of ATM can be found in [Gor01].

#### **2.3.2.5 IP layer**

IP routers delivering data packets make up the majority of the global Internet's infrastructure. IP routers can be connected using an optical core network as the physical transmission links between them. If the router port line speed is less than the granularity (basic unit) of a single wavelength, the IP data can be transmitted using SDH layer framing. A detailed explanation of IP can be found in [Lee98].

#### **2.3.2.6 Integration of the network layers**

The IP, ATM, and SDH/SONET layers can be combined and regarded as an entire network. The entire network can be seen as a set of layers, each representing a transmission system. Fig.2.11 shows a layered structure of IP over ATM over SDH/SONET network given in [Myn01].

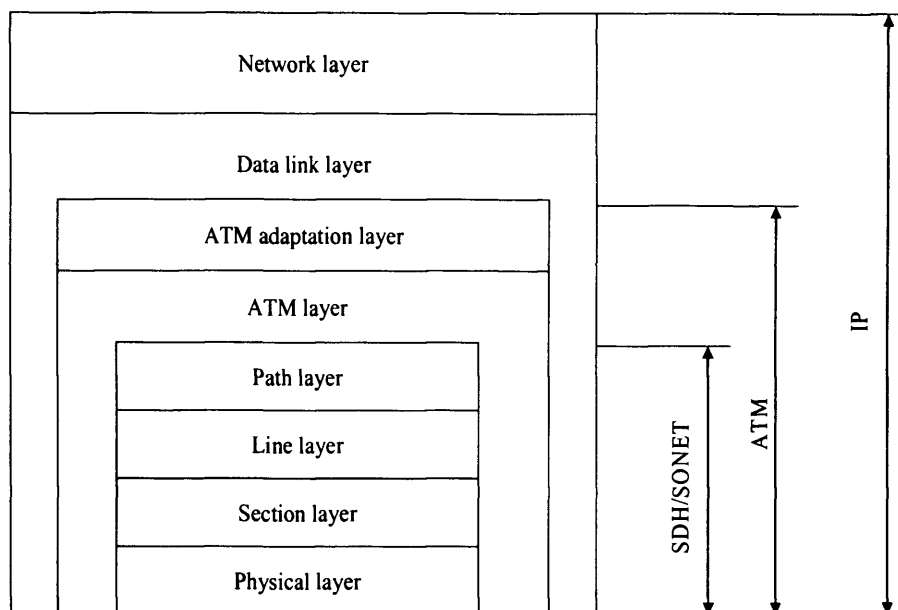


Figure 2.11 - Layered structure of IP over ATM over SDH/SONET [Myn01]

Physically, the ATM switches are connected to the SDH/SONET adapter cards, through which ATM gains access to the SDH/SONET network. A traffic data stream to an ATM network is converted into ATM cells. The ATM directly switches these cells to the SDH/SONET adapter cards. SDH/SONET converts the ATM cells into frames and transmits these frames over the network. At the destination, the SDH/SONET adapter card converts the frames back into ATM cells and hence the reverse process is performed. As for the IP transmission, IP often resides over the ATM layer, which lies over the SDH/SONET layer. In the network environment, IP routers are connected to the ATM network. IP data packets are converted into ATM cells. The cells are transmitted through an ATM network and converted back into IP packets at the periphery of the ATM network.

In general, IP packets are encapsulated into ATM cells that, in turn, are transported in SDH virtual containers. These frames are then transmitted across the optical layer using WDM techniques. A schematic integration of different layered networks is shown in Fig.2.12. In the future, as traffic in fibre-optic networks continues to grow rapidly, it becomes increasingly desirable to run IP directly over WDM optical

networks to save equipment cost on the intermediate layers such as ATM and SDH/SONET and to simplify traffic management.

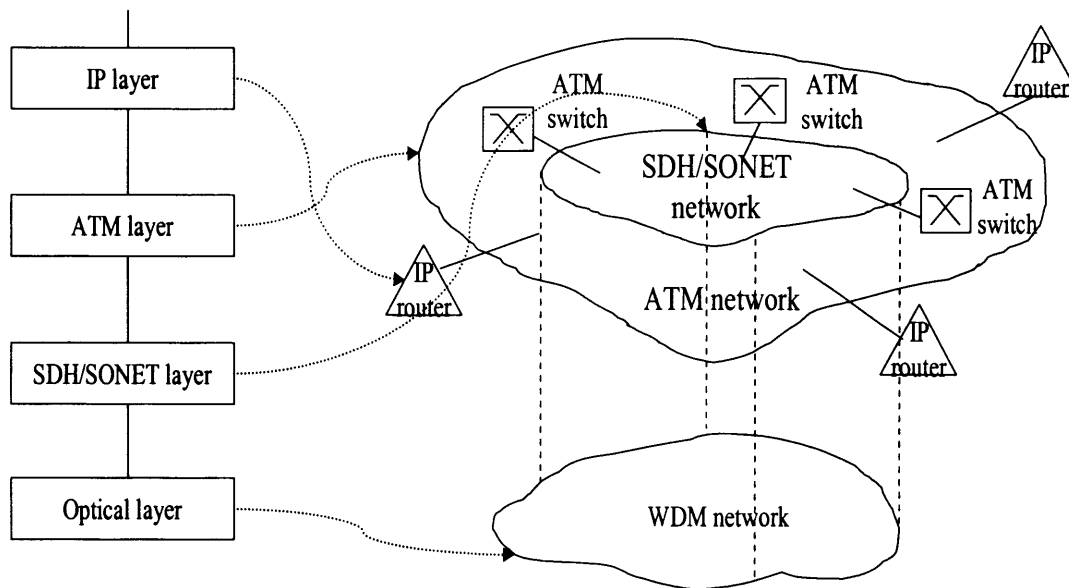


Figure 2.12 - Layered optical network architecture

### 2.3.3 Network architecture evolution

The explosive demand for bandwidth is driven by the popularity of the Internet and many other new applications including ISDN, ADSL, CATV, which provide high-speed access to the end-users' premises. This trend of huge demand for information communication, in turn, influences the development of next generation telecommunication network architectures. It also changes the nature of the telecommunication industry from voice circuit-switched services to data packet-switched services. WDM is already seen as a promising and reliable technology which employs the huge bandwidth of the silica fibres to satisfy the capacity demand. The multi-layered structure built on the current WDM network has one inherent flaw, the multiple interfaces between different layers increasing the complexity of the network administration, compromising the network reliability, and potentially increasing the equipment costs. This naturally leads to the solution of the all-optical network (AON), where one optical layer performs all the network's functions instead of multiple layers. The "data directly over optics" could potentially eliminate the unnecessary network layers and lead to a vast reduction in the cost and complexity of the network. In the last few years, much investigation has been carried out to bring about the

proposed next-generation Internet protocol (IP) over optical transport network (OTN) technology, specifically, IP over WDM. The IP-based data could be directly transmitted across the WDM based optical network as a simple two-layer structure. Attention has been focused more recently, not only on IP over WDM in long haul transmission, but also in metropolitan transmission. Along with the optical technology penetration, with the availability of gigabit throughput IP routers, the routers can be directly connected with high capacity optical equipment in order to reduce the overheads generated by the middle layers. A technology called multi-protocol label switching (MPLS) has been introduced [Nag03] to save electronic packet routing and offer fast lightpath provisioning. It could be seen that with the development of the “intelligent” optical network, more functions currently performed by the IP layer could be realised in the optical layer to keep the transparency. In the future, with more interaction between the two layers, the line between them could be less distinct. Fig.2.13 Left shows the network architecture development with time frame. Fig.2.13 Right shows the proposed next generation network architecture [Ant01].

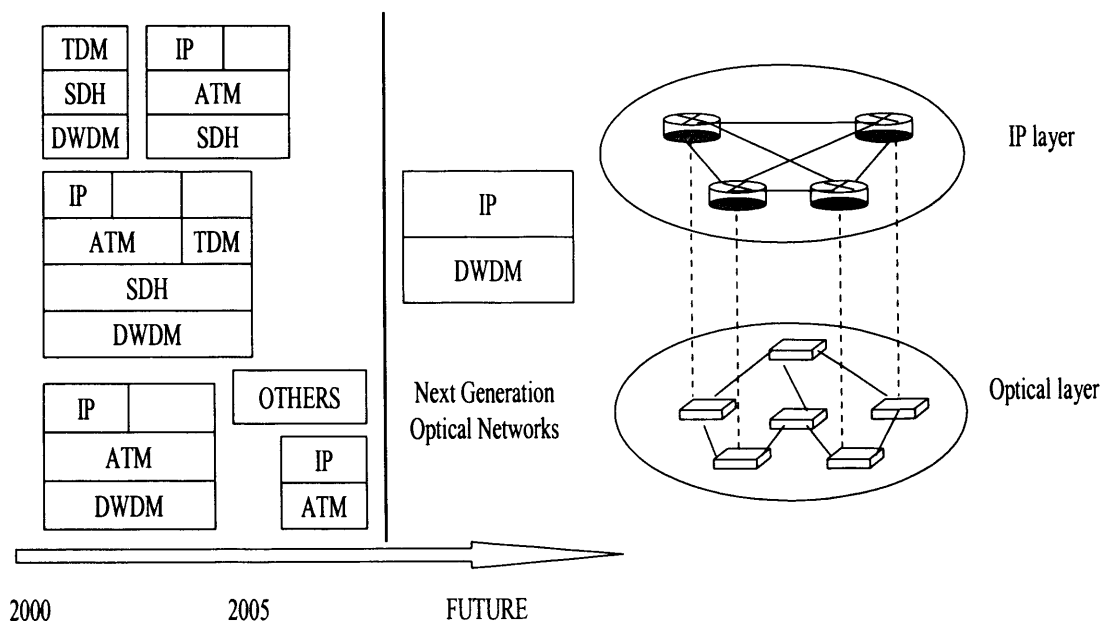


Figure 2.13 - Left: Network architecture evolution; Right: Next generation optical network architecture

## 2.4 Optical switching technology

As discussed in the previous section, with IP playing a dominant role in networking technology and advancements in WDM technology to provide tremendous bandwidth, the IP-over-WDM technology becomes a promising choice for next-generation IP networks. Three major technologies based on WDM architecture have been proposed to transport IP traffic over WDM-based optical networks. Accordingly, the IP-over-WDM networks can be classified as optical circuit switching (OCS), optical burst switching (OBS), and optical packet switching (OPS) networks. In this section the optical switching modes are discussed first, relevant switching devices and techniques are then introduced, and a forecast of optical switching evolution concludes the section.

### 2.4.1 Optical switching modes

#### 2.4.1.1 Optical circuit switching

WDM networks were initially deployed using circuit switching technology. In optical circuit-switched networks, the lightpaths are used as the optical circuits. As ATM and SDH/SONET are already deployed in the backbone networks, it is natural to route the ATM and SDH/SONET connections carrying IP traffic over the optical layer in an optical circuit-switched network. However, this leads to increased layers and larger overheads. Like traditional circuit-switched networks, OCS networks follow the three phases of “handshaking”, which include lightpath setup, information transfer, and lightpath release [Mol01]. Optical switches along the lightpath are configured before the messages are transmitted. When the transmission is completed, the destination node sends an acknowledgement to the source node. A serious disadvantage of OCS network is that the bandwidth utilization is low.

The optical layer in OCS networks provides circuit-switched lightpath services to the above layers such as IP, ATM, and SDH/SONET. Due to this nature of the OCS, there can be many forms of OCS networks, including IP-over-ATM-over-SDH/SONET-over WDM, IP-over-SDH/SONET-over-WDM, and IP-over-WDM. In IP-over-WDM, the IP packets can be directly wrapped with simple data link (SDL)



frames and routed over the optical layer, which avoids the intermediate SDH/SONET layer and saves significant overheads [Mol01].

Optical circuit switching is the current technology employed in the backbone transport networks and it is expected to remain the main switching mode in the near and medium future for core optical networks [Gea03a]. However, optical burst switching and optical packet switching have drawn more interest, because of their advantages over optical circuit switching.

#### **2.4.1.2 Optical burst switching**

Although optical packet switching is considered the most promising technology for future optical networks because of its highest resource efficiency among the three, optical burst switching (OBS) is believed to be the intermediate technology in the transformation from current OCS to future OPS, as OBS combines some advantages of both OCS and OPS.

In optical burst switching, the data is transmitted in bursts instead of packets [Qia00]. A burst is a variable or fixed length data message which is assembled by aggregating a number of IP datagram packets. In OBS, an edge router accumulates a certain amount of traffic and packs it into bursts before transmission, and only forwards them onto the core optical network when certain conditions are met. At the receiving edge router, the burst is dissembled and data is converted back to IP packets, which will be forwarded further to corresponding access networks. In this way, the OBS eases the burden in the core optical networks. In the meantime, efficient bandwidth utilization has been achieved by reserving bandwidth on a link only when the data is required to be transmitted through the link. In burst switching, a control burst will be sent out first to reserve the bandwidth for the following data burst to be transmitted [Qia00]. The data burst is sent out following a certain time interval. The control burst and data burst are sent over separate wavelength channels through the OBS network traversing a number of core network nodes before reaching the destination. At an intermediate node, the control burst is processed electronically whereas the data burst is switched optically. When reaching an intermediate node, the control burst reserves a wavelength on an outgoing fibre link for the data burst starting from the time at which

the data burst arrives until the time at which the data burst will be transmitted completely. If no wavelength is immediately available, the data burst can either be delayed by optical buffers or rejected due to lack of resources. Upon successful wavelength reservation, the control burst is forwarded to the next node along the fibre. The entire bandwidth of the wavelength is used only during the transmission of the data burst, thus efficient resource utilization is achieved.

One of the main benefits of the OBS scheme is that the requirements for large amounts of optical buffering can be avoided, as data is aggregated electronically at the edge routers and then sent out in optical bursts. Therefore, optical buffering is not needed at intermediate nodes. This is the major advantage of OBS over OPS, as for optical packet switching, a large amount of optical buffering is needed, which still requires significant development to be commercially viable. Currently, optical buffering is realised by fibre delay line techniques, requiring large amounts of fibre, switches and optical amplification.

OBS has other advantages, including the less stringent requirements on synchronisation as well as better quality of service (QoS) provisioning [Bay01]. QoS can be realised by setting priority in bursts. Bursts with high priority will be forwarded more quickly than those that are less delay-sensitive.

Several burst switching protocols have been proposed in [Qia00]. They are different in the choice of burst offset time, which is the time gap between the transmission of control burst and data burst at the source node. There are two main OBS protocols: the Tell-and-Go protocol and the Just-Enough-Time protocol. In Tell-and-Go (TAG), the data burst is transmitted immediately after the transmission of the control burst in a zero or negligible time gap. The control burst reserves the bandwidth and buffers at every node along the path for the data burst. Upon reaching a node, the data burst is buffered until the processing of the control burst is complete and the wavelength is available on the outgoing link. If no wavelength is available, the burst is lost. Otherwise, the data burst is transmitted on the reserved wavelength. When the transmission of the entire data burst is complete, the source node sends another control burst to release the wavelength being used along the path.

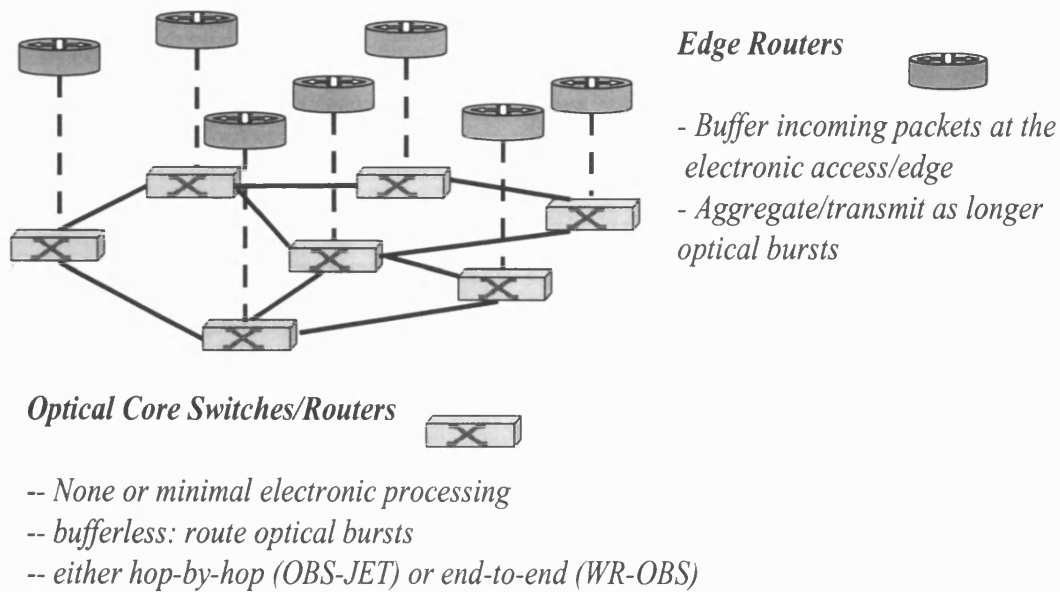


Figure 2.14 - A schematic of an optical burst switching network architecture [Bay01]

In Just-Enough-Time (JET) protocol, the wavelength is reserved for the data burst in a fixed duration specified by the prior control burst. The offset time is chosen such that when the data burst arrives at a node, the reservation is already made and a wavelength is readily available for onward transmission. Hence, there is no need to buffer the data burst at the intermediate node. There is also no bandwidth waste, as the wavelength is reserved for the duration of the data burst only. Compared with TAG, the JET is much preferred because of its buffer-free nature. Fig.2.14 shows a schematic of an optical burst switching network.

However, the JET-based optical burst switching network also has several disadvantages [Dol01]. On the one hand, the entire path reservation is not acknowledged, as the burst transmission is built on a hop-by-hop basis. On the other hand, a burst may be lost at any intermediate node, so that the QoS may not be guaranteed. A new OBS architecture termed wavelength-routed optical burst-switching (WROBS) has been proposed to overcome the shortcomings in the JET-base OBS network in [Due00], which requires end-to-end reservation to satisfy specific service criteria. The WROBS assumes a fast circuit-switched end-to-end lightpath assignment, with a guaranteed delay and requires an end-to-end acknowledgement. Fig.2.15 shows a schematic architecture of a centralised WROBS, in which lightpath allocation is performed by a central control node in the network. Details of centralised WROBS can be found in [Due02].

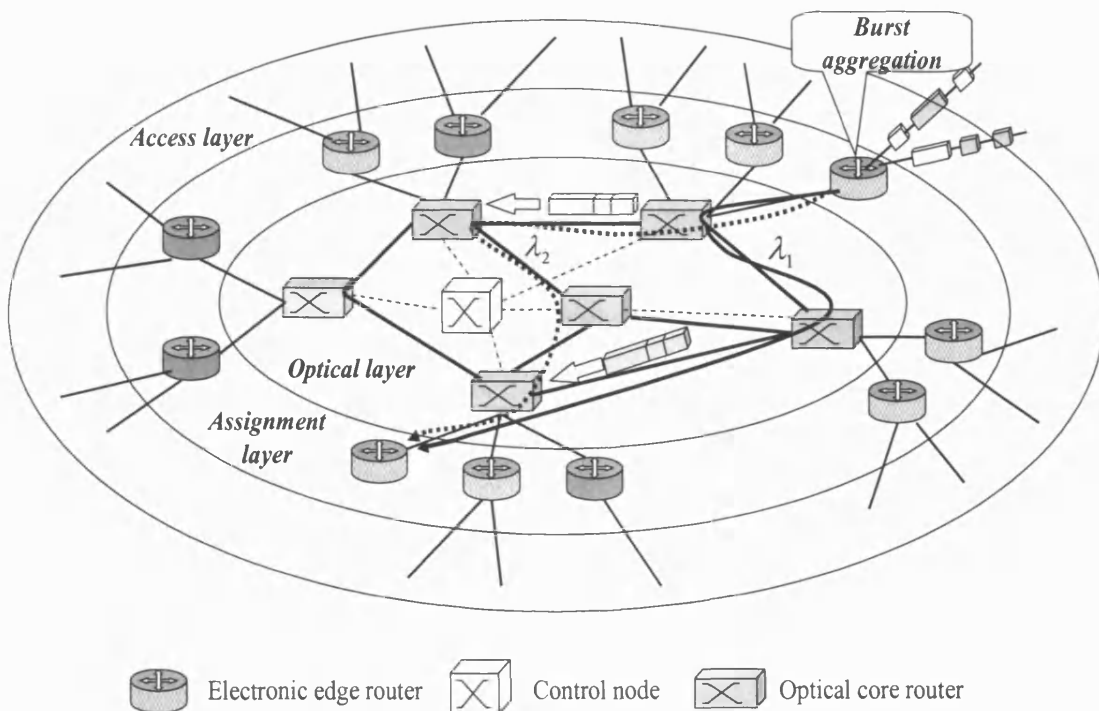


Figure 2.15 - Architecture of the wavelength-routed optical burst-switched (WROBS) network with burst aggregation at network edge and wavelength routing in the optically transparent core [Due02]

#### 2.4.1.3 Optical packet switching

With the rapid increase in the demand for capacity, optical packet switching may become more effective than optical burst switching at a certain point, as the individual

datagram can have more freedom to choose alternative routes to their destinations. In addition, in comparison to OBS networks, OPS networks are less likely to suffer the loss of large amounts of data in case of packet loss. Furthermore, it is possible to recover a small amount of lost data by error correction techniques. Packet switching is a communications paradigm in which packets are individually routed between network nodes, with no previous established communication path. This is often referred to as connectionless. Optical packet switching is the opposite of optical circuit switching or connection-oriented techniques.

The large throughput of IP routers with processing capability of terabits per second is required when implementing IP directly over WDM. However, there is a large gap between the IP routers' packet processing capability and WDM transmission capability. In order to increase the switching speed, it is essential to perform the switching in the optical domain instead of the electronic domain. This has led to huge interest in the research and development of optical packet switches [Chi00] [Yao00] [Baw02].

Optical packet switching offers connectionless packet switching, such that the lightpath is not reserved when the transmission takes place. This raises a fundamental issue in OPS concerning contention resolution, because packets from different input ports can be destined to the same output port at the same time. In general, contention resolution techniques are categorized under three types: buffering (time domain), wavelength conversion (optical domain), and deflection routing (space domain). These solutions differ in their performance, and come with advantages and disadvantages.

In [Zho03], it is shown that OPS in core networks would not be practical without a breakthrough in the research area of optical buffering technology. As mentioned briefly in the previous section, optical random access memory suitable for optical packet switches has not yet been found. Optical buffering can only be implemented using fibre delay lines (FDLs). FDLs rely on the propagation delay of the optical signal in fibres to buffer packets in time. The length of a FDL determines the amount of time for which a packet can be delayed. FDLs are bulky and not scalable, and hence cannot be included in the switching fabric due to the increased size and cost.

Wavelength conversion used as the packet contention solution is straightforward to understand. When two or more packets are competing for the same output link, if there are two or more free wavelengths, then the packets can be converted to the free wavelengths and sent to the same link without any delay. In the case of a lack of free wavelengths, the packets can be buffered.

Deflection routing uses detours when there is contention among packets. If two packets are destined to the same output link, one of them is sent to the original planned output link, whereas the other one is sent to some other free link. The drawback of this solution is that the deflected packet may travel a longer route that causes an unacceptable delay. Details of the contention solutions can be found in [Siv02].

An efficient and fast protocol is also necessary when considering IP-over-WDM in the case of OPS, as the requirement on optical buffering capacity is less strict in OPS, provided the packet size is reasonably small. However, smaller packet size means increased overhead in proportion to the payload. Therefore, a fast routing and forwarding technique such as multi-protocol label switching (MPLS), is much preferred. The use of an MPLS approach helps to minimize the cost of transition from the present circuit-switched technology to burst/packet-switched technology. In addition, QoS can be realised through the label switching, such that the class of service (CoS) can be differentiated and categorized with priority. Packets with labels enable them to be processed accordingly by the label routers. This gives “intelligence” to the optical network control and makes the all-optical network more automatic.

There have been many projects working on the optical packet switching networks and corresponding technologies, which include WASPNET (Wavelength switched packet network) [Hun99] [Chi01], IST-OPTIMIST (Optical technologies in motion for the IST programme) [Ack01] [IST05], ACT KEOPS (Keys to optical packet switching) [Ren97] [Gui98], and OPERA (optical packet experimental routing architecture) [Car98]. The details of implementation and lab demonstration of optical packet switching can be found in the above papers. Fig.2.16 shows a schematic diagram of an optical packet switching network.

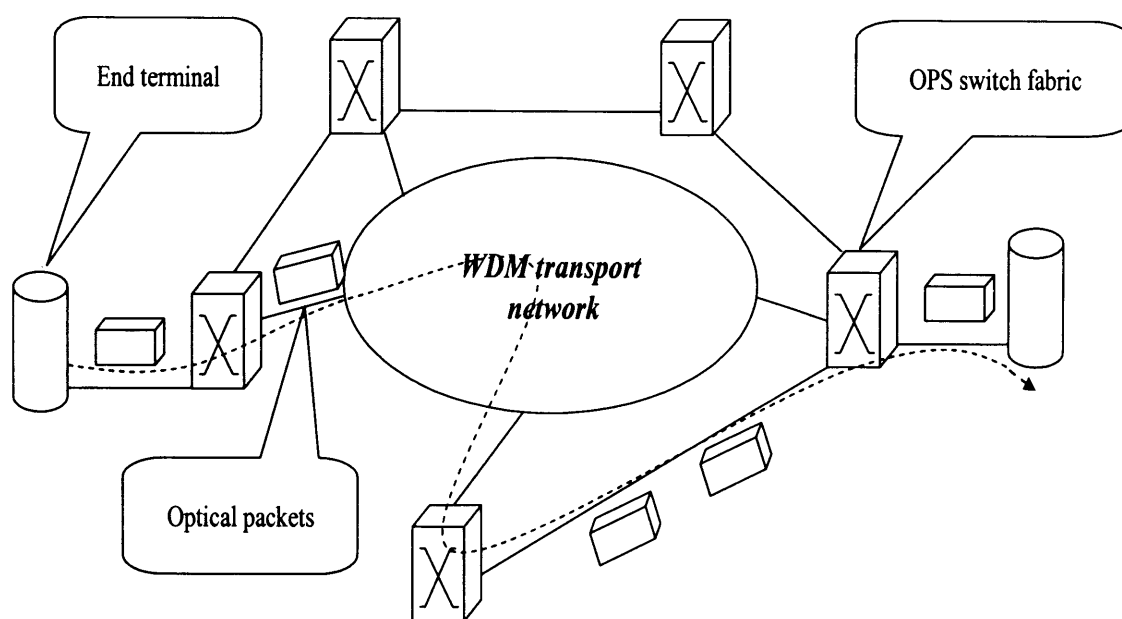


Figure 2.16 - Architecture of optical packet switching network

### 2.4.2 Optical switching devices

The term optical switch has a wide meaning, as discussed in the previous section. Optical cross-connects and optical add/drop multiplexers are examples of optical switches. An optical switch is a switching device that is able to switch and forward multiple optical input signals from input ports to output ports, eliminating the need for O-E-O conversion and vast electronic gate operations in electronic switching. In an optical network, a switch in the network node should be able to connect any input channel to any specified output channels.

A generic optical switch usually combines several logic functions: the input/output interface, the switching matrix, and the switching control. The input/output interface is responsible for splitting and combining multiple optical signals, which are usually referred to as MUX and DEMUX. The switching matrix is the core of the switches, where the switching operation takes place. In an  $N \times N$  switch, the design of the switching matrix concerns not only the blocking probability but also the cost efficiency. The switching control includes functions such as synchronous control, switching control, and label processing. Fig.2.8 has shown two examples of optical switches. A schematic diagram of general optical switch functions is shown in

Fig.2.17. With the extension of optics from transmission media to networking, optical switches have become more crucial for realising optical networks.

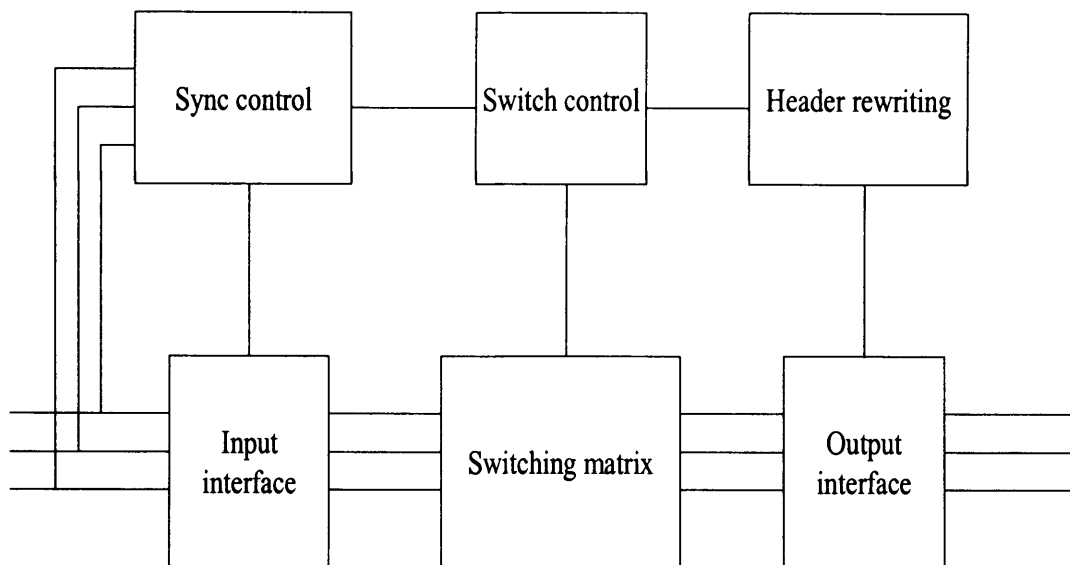


Figure 2.17 - Logic functionality of a generic optical switch

Switching optical signals can be realised using several different techniques and mechanisms. Therefore, optical switches are designed using these technologies, which include optical microelectromechanical systems (MEMS) based switching, thermal optical switching, electro-optical switching, opto-optical switching, and acousto-optic switching.

Optical MEMS are tiny devices combining optical, electrical, and mechanical functions. Currently the MEMS-based technique is the most popular one due to its low crosstalk, wavelength insensitivity, polarization insensitivity, and scalability. The optical MEMS-based switch falls into three categories. They are mirror-based switch, membrane-based switch, and planar moving wavelength-guide-based switch.

The thermal optical switch is based on the waveguide thermo-optic effect or thermal sensitive materials. The main advantages of thermal optical switch are the fast switching speed, on the order of a millisecond, and the polarization-insensitive nature. The electro-optical switch is based on the electro-optic effects. It has the advantage of fast switching speed. There are many types of electro-optical switches, which include



the LiNbO<sub>3</sub> switch [Kra02], semiconductor optical amplifier (SOA)-based switch [Gal02], liquid crystal switch [Riz98], electro-holographic (EH) optical switch [Agr99], and waveguide Bragg gratings switch [Dom97]. These electro-optical switches differ in performance in terms of switching speed, extinction ratio, and device size.

The mechanism behind opto-optical switches is the intensity-dependent nonlinear optic effect in optical waveguides. This switch is also called all-optical switch. This type of switch is much preferred due to its optical transparency, low operating power, ultra-fast operation, and high extinction ratio.

In acousto-optic switches, ultrasonic waves in different crystals are used to deflect light. The mechanism is based on the acousto-optic effect in crystals.

Technology	Loss (dB)	Crosstalk (dB)	Switching Time	Max Switch Dimension	Maturity
2-D MEMS	5	55	<10 ms	32 x 32	High
3-D MEMS	7	55	<10 ms	4000 x 4000	Low
Bulk mechanical	3	55	<10 ms	16 x16	High
Bubble-based waveguide	7.5	50	<10 ms	32 x 32	High
Liquid crystal	1	35	<10 ms	2 x 2	High
Electro-optical	8	35	<10 ns	16 x 16	Low
Thermo-optical	8	35	<10 ms	16 x 16	High
Holographic	1	35	<10 ns	64 x 64	Low
SOA	Gain	35	<10 ns	4 x 4	low

Table 2.3 – Comparison of optical switching technologies [Tza04]

The performance comparison of different optical switching technologies is shown in Tab.2.3 [Tza04].

### 2.4.3 Optical switching techniques

In the near future, the transport network will support switching fabrics based on fibre/space switching (physical ports), wavelength switching (lightpath), label/packet switching (electronic labels/headers), and time switching. With the development of additional functionalities, the conventional electronic routers/switches will be moved out of the core network to access network and become edge routers. A new type of routers that performs optical switching with high speed and large throughput will appear in the transport core.

#### 2.4.3.1 Wavelength routing

Wavelength routing is currently evolving. Wavelength routing can be seen as a special type of label switching, as the wavelength can be regarded as the “lightpath label”. It dramatically decreases the burden of the network routing algorithms by transmitting data on different routes over different pre-assigned wavelengths, so that data flow can transparently pass all the electronic switches on the way. However, wavelength-routed networks need to be carefully designed to use the wavelengths efficiently, as the number of available wavelengths is limited. Furthermore, in order to avoid wavelength contentions, some of the network nodes can be equipped with wavelength conversion facility. However, the placement of wavelength conversion in the network should be carefully considered.

#### 2.4.3.2 Fibre/space switching

The principle behind fibre/space switching is to change the direction of light beams to access an output port or multiple output ports. The difference between fibre switching and space switching is that the former focuses on redirection of lightwaves from one fibre into another, which can be realised by wavelength routing, while the latter emphasizes spatial rerouting using MEMS technology, LiNbO<sub>3</sub>-based switch elements, or SOA gate switches as discussed in the previous section. Switching technologies performing with millisecond times are not ideal for optical packet switching as they do not meet the requirements of nanosecond packet level switching.

### 2.4.3.3 Label switching

Electronic label/packet techniques are very mature and are frequently employed in current routers/switches. Generally, the mechanism of label switching is to use small-sized simple local labels instead of full and complicated headers when routing and forwarding packets/datagrams within a network. In the case of MPLS, it uses the electronic labels. Optical label switching decouples label from the payload by multiplexing it onto a sub-carrier header in the same wavelength of an optical data stream. Optical label packets can stay in the optical domain and be routed transparently through routers/switches. The label processing and switching control are performed in the electronic domain. The optical label technology significantly increases the efficiency of routing and forwarding in IP-over-WDM networks.

### 2.4.3.4 Photonic slot routing (PSR)

PSR is another type of optical switching, which is also known as optical time-division multiplexing (OTDM). PSR is a time-slotted WDM approach, whereby information streams on distinct wavelength channels are organized to form time slots that are aligned across all the wavelength channels (photonic slots). The photonic slots are treated as indivisible entities, and switched as single wavelength-transparent units of information throughout the network. In the photonic slot routing network, time is subdivided to form time slots of equal duration. A time slot can accommodate the transmission of one fixed-length packet on each wavelength. Slots are synchronized across the wavelengths to form a group of aligned packets (photonic slots) that propagates along the fibre as a whole. The function of a PSR node is to route each photonic slot as an indivisible unit of information throughout the network [Ele01].

## 2.4.4 Evolution of optical switching

It is not straightforward to forecast the evolution of optical networking with a time frame. A possible roadmap of optical networking technology with time is given in [Cin02] and shown in Fig.2.18.

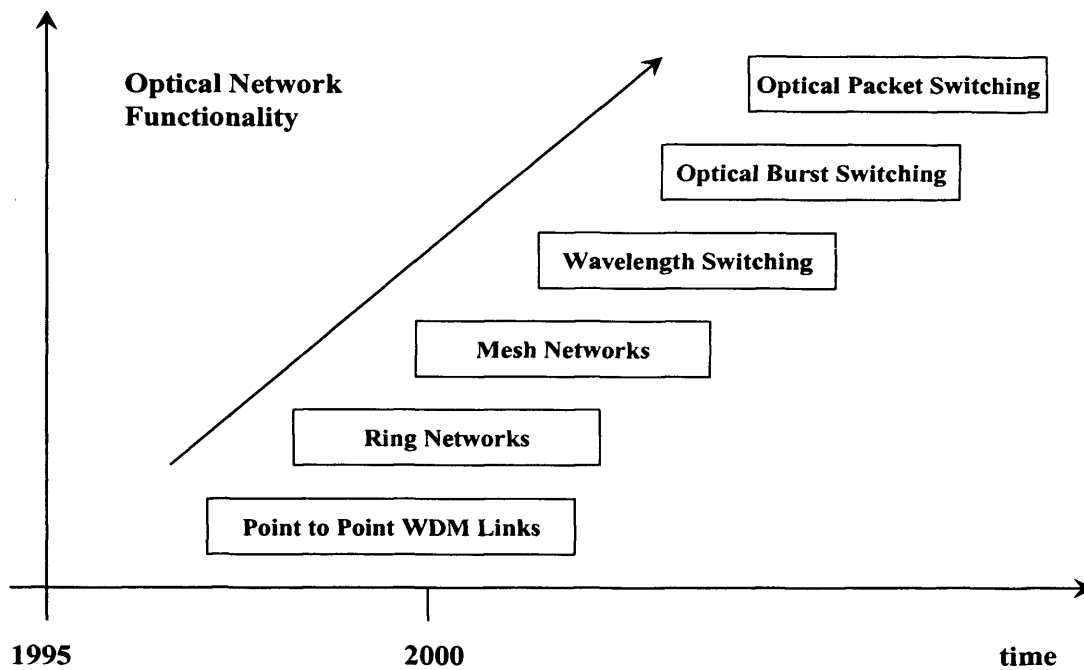


Figure 2.18 - A possible optical networking evolution road map [Cin02]

With the arrival of OADMs and OXCs, the early point-to-point WDM link system has been extended to a system that can perform certain networking functions by carrying multiple signals over a single fibre by different wavelengths. Simple ring networks were constructed on the OADMs and interconnected by OXCs. With the evolution of mesh networks, the network topology becomes more arbitrary. The development of switching technology is the key to realising optical networking functionalities. Nowadays, wavelength-routed optical networks, which are in static configurations, are often referred as WRONs [Bar97]. In static WRONs with a fairly stable traffic demand, the leased connections in the network are set up and torn down in days or weeks, while in dynamic wavelength-routed switched networks, the connections are set up in a few seconds through signalling, and resources are released immediately when they are not needed any more due to the dynamic traffic demand variations. For the dynamic wavelength-routed switching networks, there is no traffic matrix given in advance, network configuration responds to the dynamic traffic demand. The data transmission takes place after optical cross-connects are configured along the lightpath, the optical signals travel on a particular assigned wavelength or multiple

wavelengths (in the case of wavelength conversion). The wavelength is released immediately after the transmission is complete. Obviously, the dynamic wavelength-routed switching networks have a better utilization than the WRONs, as the released wavelength can be used by other traffic request, whereas the wavelengths in a particular fibre in a WRON are assigned to specific node-pair request and never released even if there is no transmission for that specific node-pair. The static configuration in WRONs seems to be advantageous for relatively steady traffic in long-distance transport network, which carry a huge amount of aggregated traffic, while in access and metropolitan networks, the dynamic wavelength-routed switching approach is more appropriate, as traffic is more unpredictable in these environments [Cin02]. The advantage of WRONs is that a connection with dedicated resources is allocated with guaranteed QoS, whereas in dynamic configuration, the connection is torn down when it is not needed, and re-established if needed again. This is useful for connections of constant bit rates, which are close to the optical channel capacity. However, with the increasing popularity of Internet, the traffic is becoming increasingly bursty (data comes in a burst pattern, not constantly but periodically), and therefore it is hard to justify setting up a whole connection to send a few bytes of data only. It will become more efficient in the future to send and forward labelled information to the destination on a hop-by-hop basis.

Accordingly, optical burst and packet switching have drawn more attention. Due to the low switching speed of optical switching elements and the lack of materials or devices for optical random access memory, optical packet switching is less preferable than optical burst switching nowadays. However, OBS is a trade-off between OPS and wavelength switching. The optical burst switching is of particular interest in the short term, while optical packet switching remains a long term research topic. The details of the two switching modes have been discussed in the previous sections.

It is estimated that in the short term future the networks will be based on dynamic wavelength-routed switching metropolitan WDM networks, while the transport core network is expected to be statically configured in the beginning, and made automatically/dynamically switched later [Cin02]. It is also expected that in the near future the packet switching will be processed electronically based probably on OBS, since the functionality of the electrical and optical layers differs significantly. Later it

will become OPS-based technology with electronic control. Eventually the all-optical alternatives will become viable.

A slow evolution from circuit-switching (wavelength switching) to packet-switching is expected particularly in the access and metropolitan part of the networks, while the transport will possibly remain circuit switched based upon either static or dynamic wavelength-routed optical networks [Cin02]. It is highly possible that the two switching techniques might co-exist for a while in the future. In [Mar03], a hybrid network is proposed to combine both circuit-switching and packet-switching technologies. Under the new proposed network architecture, the voice traffic is transmitted via dynamically allocated wavelengths in the conventional way as circuit-switched traffic. A number of wavelengths are controlled by the IP layer according to the instantaneous demand for real-time traffic. All other remaining wavelengths are used for the transport of IP traffic, which becomes free of real-time restrictions and can adopt variable-packet length, no idle bits, and best-effort schemes. As a consequence, the whole available bandwidth can be fully exploited in the hybrid network. In the IP part of the network QoS can be differentiated for various classes of packets and network reliability/survivability can be categorized for the whole hybrid network.

## 2.5 Traffic evolution in optical networks

Global telecommunication traffic is rapidly increasing. In this section, the basics of traffic granularity and grooming are first discussed. The changing nature of the traffic and traffic categories are then introduced. Following this, the importance of the traffic volume and statistics are discussed in term of network dimensioning. Finally, the traffic history, the current state, and future traffic evolution are investigated through a literature survey.

## **2.5.1 Traffic granularity and traffic grooming in optical networks**

### **2.5.1.1 Traffic granularity**

In current network architectures, the data rates carried by the different layers have a large variation. Traffic granularity is often referred to as the smallest unit of bandwidth considered at any particular layer. In the residential area, served by the access network, the granularity may come down to the conventional 64Kbit/s voice channel. In the business environment, some large commercial customers may have the entire wavelengths for data transmission at 10Gbit/s.

Sub-lambda bandwidth is the term describing transmission data rates less than the data rate carried by one complete wavelength. It is often defined as a bandwidth smaller than the standard SDH STM-16 (2.5Gbit/s) granularity. The process of aggregation and grooming for lower granularity traffic in the access and metro networks leads to optical layer wavelength with larger granularity for the optical core network. The most frequently used granularities in SDH are STM-1 (155 Mbits/s) and STM-4 (622 Mbits/s). These are popular leased line data rates for business customers. In today's networks, the granularity distribution appears with many sub-lambda granularity data streams and a few highest granularity streams.

With the rapid increase in business communications, it is expected that the leasing of bandwidth services for business customers will shift from the standard SDH traffic granularity to a fundamental unit of the whole wavelength (lambda) transmission capacity.

### **2.5.1.2 Traffic grooming**

Traffic grooming is often used to describe the process of aggregating various traffic streams to optimise capacity utilisation across multiple layers in a network. The approach of grooming includes the bundling (also known as multiplexing) of lower granularity traffic streams into high line rate streams, which can then be carried more economically. The grooming process is a fundamental technique in telecommunications. The use of time division multiplexing (TDM) to aggregate multiple streams with 64kbit/s line rate to one 40Gbit/s line rate is a typical grooming

process. In terms of WDM application, hundreds of optical channel with smaller granularities are multiplexed and grouped together onto one fibre. A detailed description of traffic grooming in the optical layer can be found in [Mod01]. Fig.2.19 shows a simple example of traffic grooming in telecommunication networks.

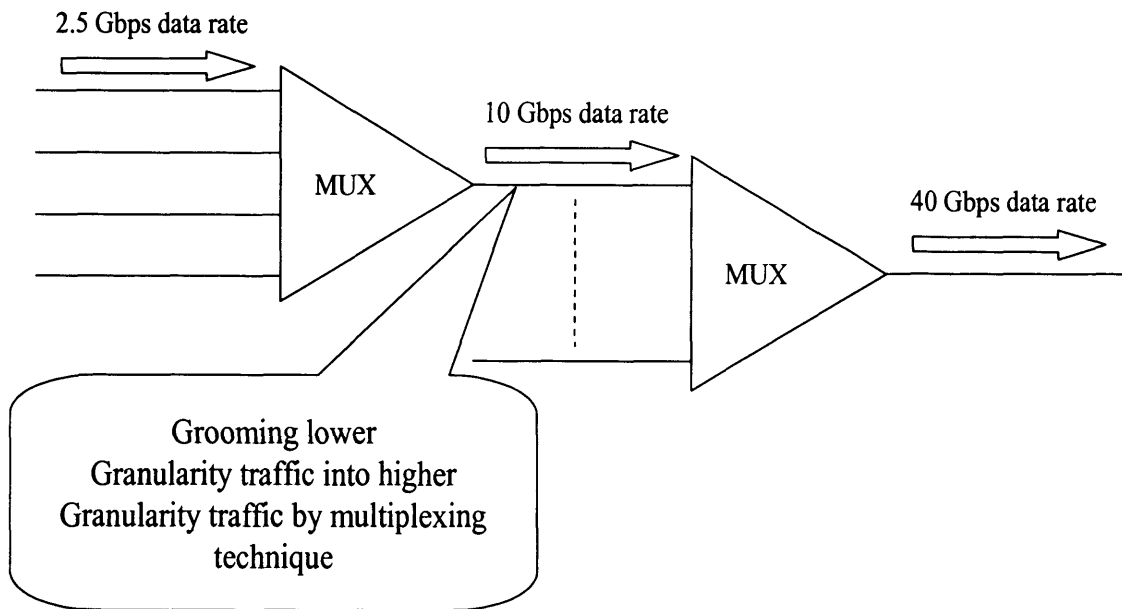


Figure 2.19 - An example of traffic grooming process

As traffic flows from the top layer to the bottom layer of the network hierarchy, the traffic grooming process is accordingly performed. It is preferable to groom the traffic at exactly one wavelength transmission rate (e.g. 2.5Gbit/s) so that the signal can be carried directly on the wavelength. If the data rate of the tributary channels is known in advance, the process of traffic grooming will determine the quantity and distribution of lightpaths required in the optical layer.

## 2.5.2 Traffic nature description

### 2.5.2.1 Traffic nature development

Telecommunication traffic has been experiencing a dramatic change in recent years. From the early years of telephony until the early 1990's, voice traffic dominated the telecommunication networks. However, with the arrival of the Internet, the traffic has



begun to change from being voice-centric to data-centric. Voice traffic is gradually becoming a marginal player in today's data-centric networks. With the development of Voice-over-IP (VoIP) related techniques, the future telecommunication traffic may become pure IP data traffic. Behind this phenomenon, traffic demand growth, development of new services, and advances in technology are the main drivers pushing the change of the nature of the traffic. Each factor influences the traffic in a different way. Furthermore, the connections among the three have a combinational impact on traffic evolution. The technology advances result in cost reductions, which, in turn, stimulate the traffic demand growth and encourage the development of various services [Say02]. The new services include peer-to-peer downloading, video on demand (VOD), and cable television (CATV). By the end of year 1999, the volume of data traffic has been reported to have taken the lead over conventional voice traffic in the world's telecommunications networks [Muk00]. With its continuing exponential growth, it is likely that data traffic will dominate over voice traffic in the foreseeable future. The takeover of data traffic will naturally lead to the design of various future network architectures to carry the data-centric traffic instead of the conventional voice-centric telecommunication network.

#### **2.5.2.2 Traffic categorization**

With the development of Internet-based applications and the fast convergence of mobile data with landline data, telecommunication traffic has become more and more dynamic and unpredictable. In the core optical transport networks, the traffic load may be static, dynamic, or partially dynamic. With static load, the traffic matrix is a fixed set of demands. The volume for each network node to every other network node is clearly described by the traffic matrix. Currently, optical layer traffic has a long holding time that lasts for several months and even years. Static traffic is considered as a known-in-advance and important assumption in the design of wavelength-routed optical networks (WRONs) [Bar97]. In static WRONs, the set of lightpaths are assigned along certain physical route across the network topology according to some algorithms in order to reduce the maximum wavelength requirement in the fibre. No blocking is allowed in this type of network.

Whereas when traffic is dynamic, traffic requests arrive in a sequential order and then are routed accordingly across the network. When routing the traffic request, the lightpath is assigned dynamically according to the network status. A physical path is configured using intermediate node switches and an available wavelength, forming a temporary lightpath, which is calculated before the transmission takes place. The temporary lightpath is released and torn down after the transmission is completed. The wavelength becomes available again for future lightpath requests. In the dynamic wavelength-routed optical networks, the dynamic traffic demands may experience blocking if there is not sufficient capacity, specifically the available wavelengths, to accommodate the request. The dynamic allocation of lightpaths is more efficient than in static WRONs in terms of capacity utilisation. With rapid traffic evolution, more dynamism will be introduced in the optical core networks as described in [Ack01] [Cin02]. Dynamic traffic is expected to dominate transport networks in the near future. The currently deployed static WRONs will then likely be transformed into dynamic wavelength-routed optical networks [Due02] [Ack01] and possibly further into optical packet-switched networks to match the traffic dynamics.

### **2.5.3 Network dimensioning with traffic consideration**

Network dimensioning is used to describe the process of balancing network cost, reliability, survivability, and flexibility whilst carrying a certain volume of required traffic. Network dimensioning is a key capacity planning discipline. Poor network dimensioning will result in wasted capital, while a dearth of capacity will adversely impact service agreements, whereas good network dimensioning leads to an optimally sized network, which balances the requirements of quality and resilience against cost control.

Detailed network dimensioning usually includes the following procedures: determining the appropriate size requirement for the network, whether it is an existing network or a planned deployment; defining key inputs for the dimensioning exercise, such as a traffic demand matrix, routing configuration, network topology, resilience requirements; optimising the routing of traffic by tuning the routing metrics and using techniques such as traffic engineering; defining a bandwidth augmentation strategy;

characterising the network load and ensuring the sizing accounts for exceptional demand.

The traditional process of network dimensioning is usually based upon a static traffic pattern, which is a pre-defined traffic matrix. The traffic volume and pattern defined for each node-pair are empirically estimated from historical data. Fig.2.20 shows the process of network dimensioning with inputs and outputs [Gea03a]. The input parameters include the traffic matrix, equipment costs, and network topology in terms of nodes and links. The process of dimensioning determines the equipment required at each node and at links, which include the end terminals, the switches, the transponders, the line systems, and the amplifiers. The output of the network dimensioning is the ultimate network design. The dimensioning process is also dependent on the carefully chosen network architecture and survivability scheme [Gea03a].

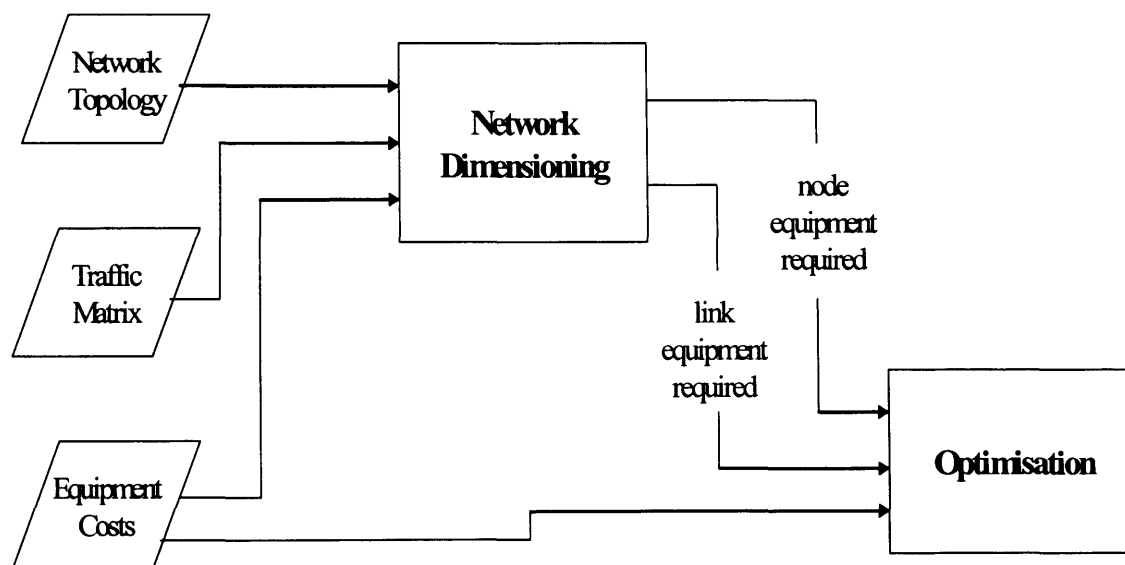


Figure 2.20 - Network dimensioning and optimisation process [Gea03a]

Many studies have been carried out on optical network dimensioning and planning. Network planning refers to network dimensioning for the long term. Network planning usually considers the period up to the time horizon of the network investment, taking the future evolution of network equipment and traffic requirements into account. A planning approach for optical transport networks carrying static traffic using a lightpath rerouting process is proposed in [Con05]. A Pan-European network

was studied for dimensioning with future estimated traffic demand in [Gur04]. Dimensioning optical networks under traffic growth models are studied in [Nay03]. A simple methodology for optimizing long-haul optical networks was presented analysing a variety of network architecture with several restoration schemes [Sai03]. [Ver03] [Gea01] and [Mau02] have considered network dimensioning under traffic uncertainty and traffic pattern changes. Both [Con02] and [Cas02] have considered dimensioning the packet-switching in next generation optical networks. It is suggested in [Gry01] that long-term planning should be broken into short multi-period optimisation with consideration of statistical traffic models and rapid technological innovations.

### 2.5.4 Traffic history and the current state

As described in previous sections, data traffic in the world's networks had overtaken voice traffic by the end of year 1999. Fig.2.21 shows the ratio between voice traffic and data traffic reported by most telecommunications carriers based on the past and projected future growth for the period of 1991-2003 at the end of 2000 [Muk00].

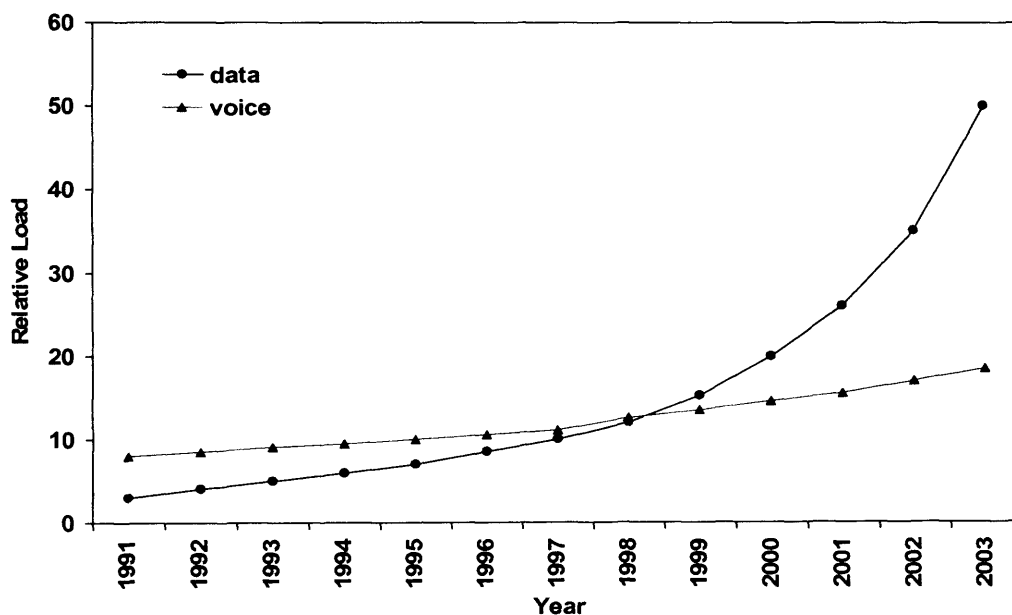


Figure 2.21 - Past and projected future growth of data and voice traffic in year 2000 [Muk00]

In [Odl03], data was collected from different US networks for the period of 1990-2002, and is shown in Tab.2.4, and is also plotted in Fig.2.22. At the time of writing

this thesis, this is the most comprehensive collection of data and network traffic. It is stated in [Odl03] that the popular assumption of traffic growth in North American backbone networks, that rates are doubling every 3-4 months, which was widely mentioned in many papers and articles [Odl03], was actually correct only for a short period in 1995-1996. It is suggested that future growth rates are uncertain, but it is estimated that the future growth rate will be close to a doubling each year for the remainder of this decade [Odl03].

Year	Data transfer	Average bit rate
	TB/month	[Gb/s]
1990	1.0	0.003
1991	2.0	0.007
1992	4.4	0.015
1993	8.3	0.028
1994	16.3	0.055
1995	155.9	0.529
1996	1,500	5.09
1997	2,500 – 4,000	8.5 – 13.6
1998	5,000 – 8,000	17.0 – 27.1
1999	10,000 – 16,000	33.9 – 54.3
2000	20,000 – 35,000	67.9 – 118.7
2001	40,000 – 70,000	135.8 – 237.4
2002	80,000 – 140,000	271.6 – 474.8

Table 2.4 – Traffic growth on US Internet backbones in the period of 1990-2002  
[Odl03]

The traffic shown in the table is the total traffic transported during December of each year. TB/month is the number of terabytes transported in that month and is converted into Gbit/s average bit rate. The conversion is based on the approximation of 1 TB/month equivalent to 3.4 Mbit/s average bit rate. The numbers given between 1997 and 2002 are only approximate ranges in the format of min-max due to the uncertainty in measurement.

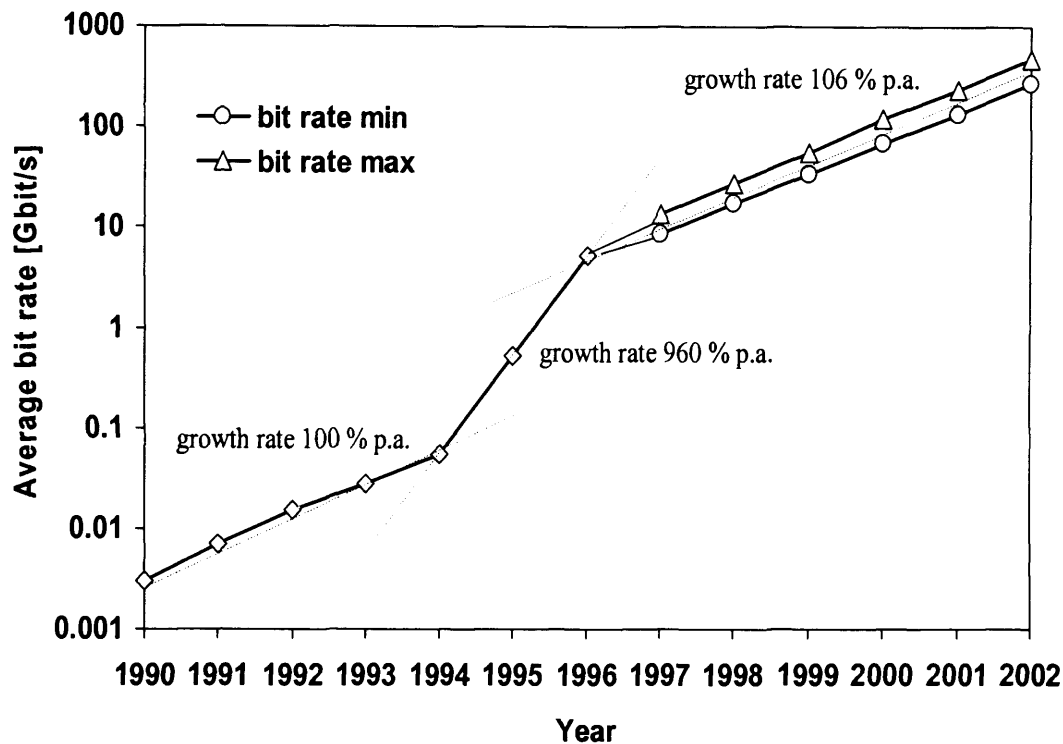


Figure 2.22 – Internet traffic growth from the US transport backbones in the period of 1990-2002 according to data in [Odl03]

It can be seen that the growth rate of Internet traffic was reasonably stable from 1990-1994 with approximately 100% growth each year. Beginning in the year 1995, the Internet traffic growth rate experienced a dramatic increase by nearly 1000% p.a. However, the increased growth rate lasted for only 2 years until the end of 1996. From the start of 1997, the traffic growth rate returned to its old state of the period of 1990-1994 with an approximate 106% p.a. up to the year 2002. It should be noted that not only the volume of the Internet traffic growth is uncertain, but also the pattern of traffic distribution. With the increasing popularity of the new peer-to-peer (P2P) based Internet applications, it is more difficult to predict where and when the traffic 'hot spots' may appear in the network. The P2P technology brings much more uncertainties to the Internet backbone transport network [Odl03]. The estimation and analysis of Internet traffic growth in backbone transport network is crucial in determining the future possible demand, the required transmission capacity, and the related equipment, which may ultimately lead to the design of future network

architectures that can better accommodate the future traffic volume growth and future pattern of traffic distribution.

### 2.5.5 Traffic evolution and estimation

Fig.2.23 shows the forecast of traffic growth in the Pan-European network given in [Gur04].

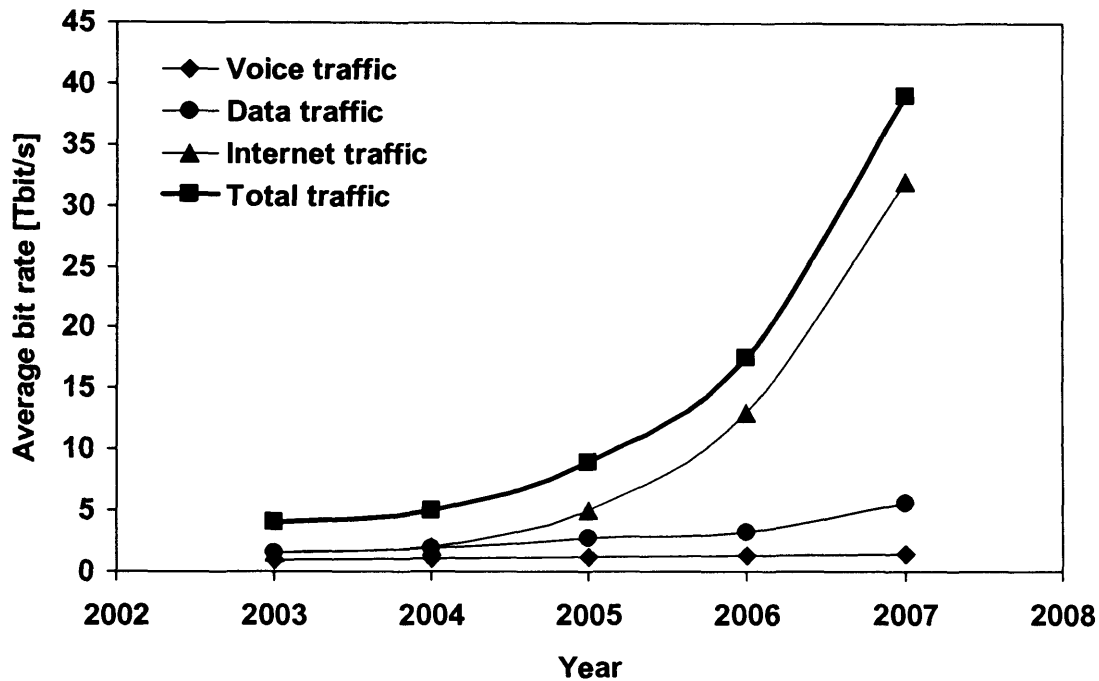


Figure 2.23 - Estimated traffic evolution in Pan-European Network [Gur04]

The load estimation is based on the proposed Pan-European network topology in project COST 266 [Gur04] [Kuc04] for the forthcoming years. The traffic demands are categorized as voice traffic, transaction data traffic, and Internet traffic with corresponding estimated growth rate at 10% p.a., 34% p.a., and 150% p.a. respectively according to [Mae02]. It can be seen that the Internet traffic in Europe will reach roughly the same amount as in the United States, and the total traffic amount in the transport core network will reach nearly 10 Tbit/s by the end of 2005.

In [Kec00], a pessimistic forecast on the growth of data traffic is shown as 30% p.a. before optical communications started to thrive and made a lasting impact in the 1970s. Thus, it is reasonable to forecast the future Internet traffic growth within the

rate of 30% - 100% p.a. and the future voice traffic growth with in the rate of 7%-10% p.a. Fig.2.24 shows the expected traffic growth in the United States from the end of year 2002 till the end of the decade as continuous estimation for Fig.2.22.

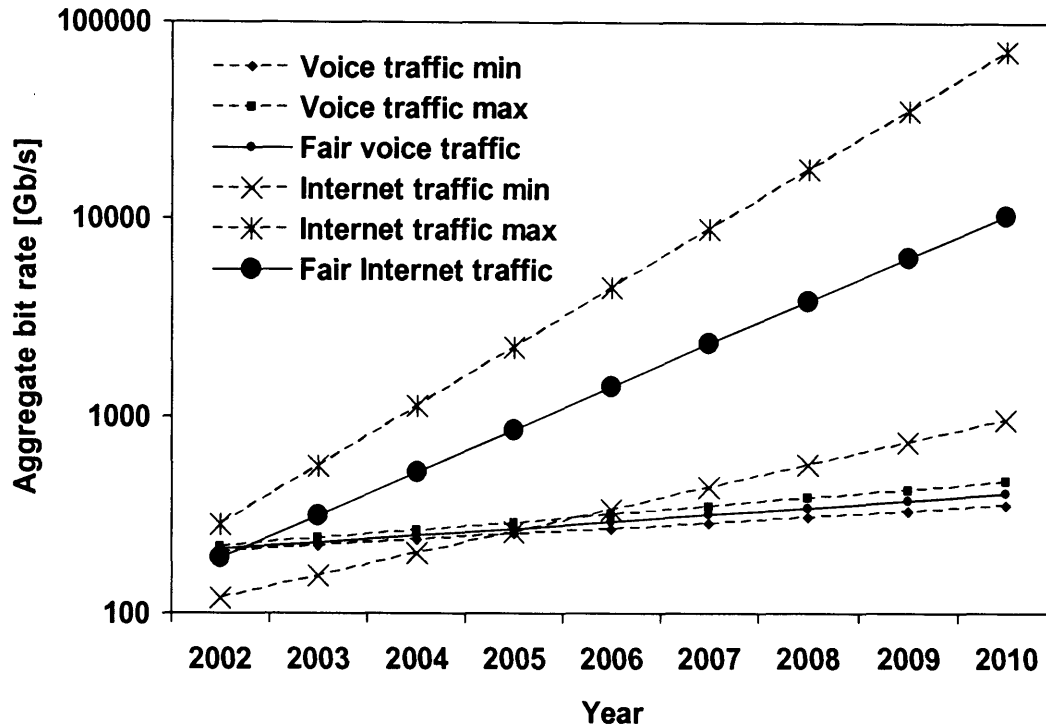


Figure 2.24 - Aggregate voice and Internet traffic growth in the period of 2002-2010 in United States

The data shown in Fig.2.24 gives the comparison of the volume forecasts for both voice and Internet traffic. The starting data in the year of 2002 is calculated from the minimum value in [Cof02] that 70 Gbit/s for Internet and 179 Gb/s for voice. The fair traffic estimation is based on the average growth rate between the optimistic and pessimistic for Internet traffic and voice traffic at 65% p.a. and 8.5% p.a. respectively.

It is essential for future optical transport networks to be equipped with the ability to cope with large amounts of both data traffic and the conventional voice traffic simultaneously. A major difference between the two types of traffic is that voice traffic is time-sensitive whereas, data traffic, in many cases, is not. Hence, it is necessary for the transition of the voice-oriented transport network to data-oriented network to guarantee QoS for the voice traffic, as the voice traffic still accounts for a large fraction of operators' revenues. This is highlighted by figures from the year



2000 that voice traffic generated \$300 billion revenue compared with just \$25 billion revenue from Internet services [Cof02]. Besides the traffic volumes, the uncertainty of traffic pattern variations is expected to increase with the rapid development of new data-based applications, as described in [Odl03]. It is therefore necessary for any future optical network architectures to be able to accommodate the increase in traffic volume, as well as the uncertainty in the traffic distribution patterns.

## 2.6 Challenges from traffic dynamics

It is shown in [Mai00] that the challenge of dealing with dynamic traffic loads will become increasingly important in the future. With the rapid traffic pattern changes and significant increase of bandwidth demands, WDM optical network design based on static-traffic is no longer easily applicable [Mai00] [Hal01]. It is expected that the core optical backbone network will evolve from a static circuit-switched optical network [Bar97], to a much more dynamic network such that the bandwidth must be provided in a more flexible manner [Hal01]. Hence the future optical network architecture of dynamic wavelength-routed optical network [Ack01], optical burst switching based WDM systems [Qia99], and optical packet switching based WDM systems [Dai90] were proposed to provide the flexible resource provisioning and efficient resource utilization for the traffic dynamics.

### 2.6.1 Challenges from uncertainties

Both the future volume of voice traffic and the Internet traffic are relatively easy to calculate with estimated growth rate based on the historical data as clearly described in section 2.5, whereas the traffic distributions and its variations are more difficult to estimate, especially for the Internet traffic. With the dynamic and random nature of IP traffic [Odl03], it will become more difficult to estimate the possible traffic congestions i.e. 'hot spot' area. Hence the performance of optical networks may vary significantly under different traffic patterns. The stable performance of the optical networks may not be sustained with the unexpected traffic pattern variations.

The traffic dynamics are taken into consideration in many studies in recent years. In the traffic model studies, dynamic factors are introduced. In some detailed network

performance analysis, dynamic traffic models are integrated to test the robustness of the network to unexpected load conditions. In the dimensioning, planning, and design of optical networks, the network resources are judged according to the cost associated with different traffic loads. In the study of routing and wavelength assignment (RWA) algorithms, many studies have been carried out to investigate the network performance assuming both static and variable traffic conditions.

## **2.6.2 Previous work dealing with traffic uncertainties**

### **2.6.2.1 Traffic model studies**

In [Vau03], a traffic model featuring traffic demand estimations with application-specific growth projections and detailed demand-to-working network capacity conversion factors is proposed and can be further applied to both long haul and metropolitan networks. The paper claims 85% agreement with actual network data which was obtained, and confirms the dominance of Internet applications. In [Dwi00], a traffic model is proposed to estimate network parameters that are useful to determine equipment sizing, functionality, and requirements. The model is based on estimated growth rate with three categories of traffic: voice traffic, transaction data traffic, and Internet traffic. Another traffic model was given in [Sin94] to estimate the telephony traffic in the European area, which introduces penetration factors to improve the previous model based on population and distance. In [Pax95], it was pointed out that the conventional traffic modelling based on the Poisson process may not reflect the real traffic dynamics in purely IP data network. The paper employed two different methods to generate the self-similar behaviour for TCP, TELNET, and FTP data and suggested that the Poisson model is not suitable when considering wide area data traffic, since traffic in wide area networks tends to show the nature of heavy-tail and long-range dependence.

### **2.6.2.2 Performance analysis studies**

In [Hua02], the performance of the PETAWEB optical network architecture was analysed. The effect of traffic on the behaviour of the protocols and the performance of the network was investigated by applying several traffic models. The analysis

employed a traffic model that can simulate the self-similar behaviour of the IP network. It was argued that the conventional modelling of network traffic based on Poisson model may not be appropriate for IP-dominant networks.

### 2.6.2.3 Network dimensioning, planning, and design studies

In [Sha04], the network dimensioning was performed taking uncertain traffic demand into consideration, without the resource control mechanisms in the IP network. The distribution of traffic demand was studied and the level of traffic demand variability was built using a statistical model. In [Gea03b], a methodology was proposed which can quantify the effects of traffic uncertainty on the static network design cost and its robustness in terms of traffic carrying capability. Both traffic volume and distribution uncertainties are included, based on the non-uniform traffic model proposed and analysed in [Gea01]. The model, based on a statistical correlation, is implemented to estimate the forecasted traffic matrix. [Mau02] further employed the traffic model proposed in [Gea01] to dimension circuit-switched backbone transport networks. The static traffic matrix is replaced by a matrix with random variables for the predicted traffic. In this paper, for the first time in the literature, the concept of transport network robustness to unexpected variations of the traffic patterns was presented. However, the authors only considered the static wavelength-routed optical network design and employed the traffic uncertainty associated with a Pan-European network topology. In [Leu02], a similar concept of the network's ability to withstand error in the demand forecast is studied in the case of static circuit-switched optical networks with path protection and link restoration. It is argued that the traffic uncertainty model proposed in [Gea01] cannot describe some of the extreme traffic scenarios. A new metric, termed Pattern Forecast Accuracy, was proposed to measure the demand errors with original traffic matrix. In [Gry01], novel methodologies based on stochastic traffic modelling, robustness, and multi-period optimisation were proposed for the long-term planning of static wavelength-routed optical networks. The methodology proposed not only copes with the fast technological innovations but also the increasing degree of uncertainty. However, this work considers to a greater extent the uncertain environment of technological and economic development, rather than future traffic load uncertainties. In [Ass03], physical topology design was considered for the transport network in the static case. The traffic matrix was originally

calculated based on many factors including population of the state, utilization factor in that state, distance between states, and a proportionality factor. Both uniform traffic matrix and a non-uniform asymmetric traffic matrix were used to test the physical topology design. In [Gur04], a Pan-European network model was considered and dimensioned using a traffic model estimation technique proposed in [Dwi00].

With the development of IP traffic, many studies have been carried out in designing IP-dominant future optical network architecture with traffic uncertainties. In [Cas02], a detailed model for all-optical WDM photonic packet-switched networks was presented and the requirements for buffer size and link dimensions were analysed. The source-destination traffic matrix was constructed such that each cell of the traffic matrix was a percentage of the total capacity per network node, and hence it can be envisioned as the probability of successfully sending a packet from source to destination. In [Nay03], a novel traffic growth model was considered in the dimensioning of the dynamic optical transport network, instead of the traditionally used static traffic matrix, to simulate the time-varying nature of the traffic. The proposed dimensioning method is based on a non-linear optimization model with cost minimization as the objective, and route exhaustion probabilities as the constraints. Thus, the capacities of a large optical network with time-varying traffic arrivals can be designed so that the exhaustion probability of any route is less than a threshold value at the time of interest.

#### **2.6.2.4 Routing and wavelength assignment studies**

In the investigation of routing and wavelength allocation algorithms, many studies have been carried out to assess the performance of RWA algorithms not only in static traffic environments but also in dynamic environments. In [Lee04], the RWA problem in wavelength-routed WDM-based network under both uniform and non-uniform traffic models was studied. An adaptive RWA algorithm based on traffic load information was proposed and shown to have better performance than other adaptive RWA algorithms. In [Wan03], dynamic routing and wavelength assignment issues in WDM optical networks were investigated for self-similar traffic for the first time. In addition, differences were presented to compare the dynamic performance for self-similar traffic models and for the Poisson traffic models. In [Aci03], the dynamic

routing design was addressed in the context of traffic forecast uncertainty for the first time. It was assumed that the forecast errors were always present during network design, either from overestimation or underestimation of future network load. A capacity management model based on load forecast and using the dynamic routing for the correction of forecast errors was presented. In [Sen01], the RWA was first investigated for optical passive star networks with non-uniform traffic load. Several non-uniform traffic matrices were given which made the logical design computationally hard. The proposed RWA algorithm showed improvement in the network performance. In [Nar00], a novel dynamic traffic model was proposed to emulate the dynamics in packet networks. It was stated that when traffic was static, deriving the optimal logical topology for a given traffic pattern was known to be NP-complete. It argued that previous work on reconfiguration proposed heuristic algorithms to determine the “best” logical topology for the given traffic pattern may be extremely disruptive with every change in the dynamic traffic. The proposed traffic model assumed that the traffic matrix changes with a set time period around the originally static traffic matrix. A load balancing algorithm was proposed to minimize network delay with the dynamic traffic loads. In [Str97], the influence of end-to-end protection on the wavelength conversion gain in all-optical networks under dynamic traffic conditions was investigated. In [Niz97], a dynamic reconfiguring tool for improving the robustness of optical transport network was proposed. The investigation was carried out for both a uniform traffic matrix and a quasi-uniform traffic matrix.

### 2.6.3 Existing problems and research initiative

In the literature, the concept of robust network design to future unpredictable traffic pattern changes has been proposed. However, the work has focused on the dimensioning process in static wavelength-routed optical networks [Gea01]. Many other studies considering traffic dynamics, including non-uniform traffic, time-varying traffic, and asymmetric traffic have been carried out, but few of these studies considered the robustness to dynamic traffic pattern changes in dynamic wavelength-routed, fast circuit-switched optical networks. Hence, in this thesis, the robustness of dynamic wavelength-routed optical network to future unpredictable traffic pattern

variations is studied for the first time. The capability of dynamic wavelength-routed optical networks to adapt to traffic distribution changes is investigated in depth.

The design of static wavelength-routed networks can be relatively simple for planning to satisfy fixed, known demand patterns with minimal agility and cost. In real networks, however, the process of network planning is generally an ongoing process, with the network having a low level of fill at day one and the operator selling capacity and expanding the network incrementally. While this minimises short term costs, it generally leads to inefficient use of resources, stranded capacity and higher overall costs. Building the dynamic wavelength-routed optical network with additional wavelength and connection agility, through the use of wavelength tunable transmitters and receivers and switched photonic cross-connects and optical add-drop multiplexers may allow more efficient use of resources and lower long term costs, but the higher initial cost may be difficult to justify against future unknown traffic revenues. Thus in this thesis, dynamic wavelength-routed optical networks are considered, to answer the question, how can the network robustness to traffic forecast errors be quantified and maximised, allowing the cost of additional wavelength and connection agility to be justified?

In the networks considered in this thesis, the data channel (lightpath) is set up upon connection request arrival and is then torn down once the transmission is completed. The network resources are hence saved for future lightpath requests. The network dynamically responds to demands and hence offers improved utilization efficiency compared to static WRONs. The problem of how to guarantee the network robustness to future unknown traffic dynamics is investigated.

With the development of wavelength routing, all-optical mesh networks will appear very soon in the future. In mesh networks, the network nodes usually take the position of major cities, whereas the physical links that connect each network node may be chosen with more flexibility, according to the physical distance, the technology, the management, and the cost. Fig.2.25 shows similar network designs with different physical link connections. It is thus essential when considering different network designs to obtain the topology that has the desirable tolerance to any future uncertain

traffic patterns. We term the network's capability to accommodate unpredictable traffic pattern variations the 'traffic forecast tolerance'.

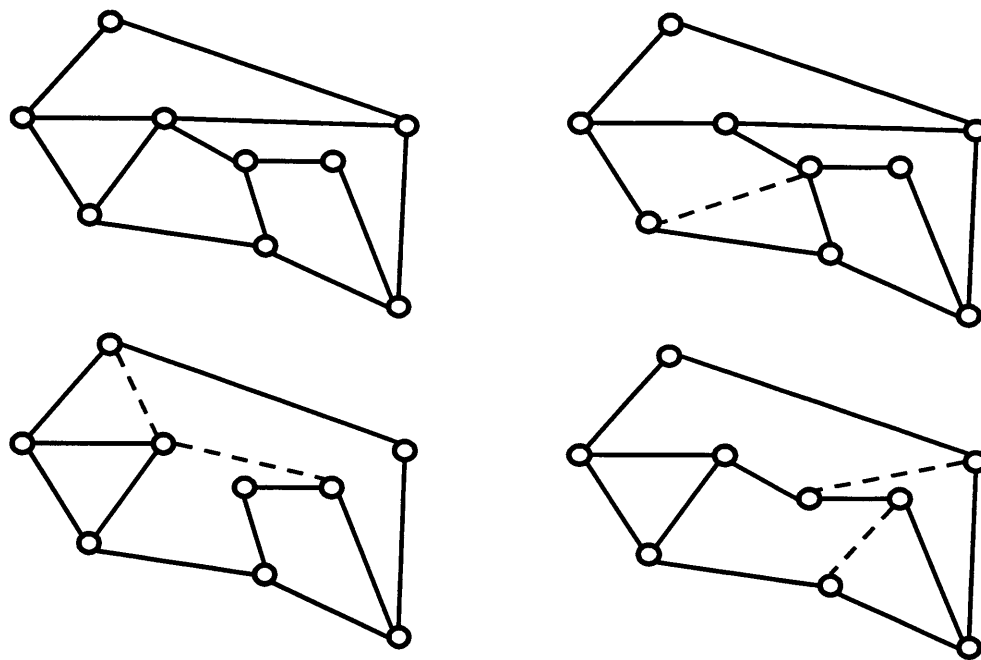


Figure 2.25 - Network topology designs with similar physical layout under same Network dimensioning

It is desirable for network operators to choose the network topology with the highest forecast tolerance when considering different networks that are designed under conditions of the similar physical layout, the same network dimensioning conditions, and the same network resources. Hence in the course of this PhD research project, the aims were:

- To quantify the nature of traffic forecast tolerance for any network topology that allows direct comparison of different network designs under the same traffic conditions
- To investigate the influencing factors which affect the tolerance of the network
- To investigate how to improve the network tolerance

The results of this research can be used to design and expand robust networks, with the capability to carry unpredictable traffic patterns that is higher than other similar network designs with the same network dimensioning.

## **2.7 Summary**

In this chapter, the basics of optical networking were discussed. The future evolution of optical networking was introduced, considering several optical network architecture candidates. Following a description of optical technologies used in the realisation of wavelength-routed optical networks, the history and current state of traffic loads, and traffic load forecasts were presented. It is estimated that traffic loads will not only increase, but will become increasingly dynamic in the optical core networks. Dealing with the unpredictable traffic pattern variations becomes an important issue.

This thesis describes a detailed investigation of dynamic wavelength-routed optical network robustness to unpredictable traffic pattern variations.



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## **Chapter 3 Investigation of Traffic Forecast Tolerance in Wavelength-Routed Optical Networks**

### **3.1 Introduction**

As explained in Section 2.6.3, traffic forecast tolerance is defined as the capability of a network to accommodate unknown traffic pattern variations. Similar ideas of constructing optical networks with robustness to traffic variations have been proposed and investigated previously, mainly in the network dimensioning and planning field. Studies of robust network design in terms of both demand and pattern have been carried out as briefly described in Section 2.6.2.3.

In [Gea01] and [Gea03], the author described a methodology to carry out optical network planning with traffic forecast uncertainty. The network robustness is assessed in five steps. The predicted traffic is first defined with the network topology. Following the prediction of the traffic patterns, the network is then designed for this prediction, and, in particular, traffic routing and the allocation of line systems are performed so that the optimised DWDM systems give the minimum cost solution. After dimensioning the network for the expected traffic, the ‘actual’ traffic is randomly generated. Routing the randomly generated ‘actual’ traffic is then carried out as much as possible over the network designed for the ‘predicted’ traffic. Hence, the volume of the ‘actual’ traffic which could not be routed will be recorded for further analysis. The investigations focused on the tradeoffs between minimum network cost and network flexibility against future traffic uncertainty. The result can be used to test the network design, in particular, the probability that any given demand can be routed based upon the estimated accuracy of the traffic forecast. The work is focused on the optical core network taking both traffic volume and distribution uncertainties into consideration.

In [Leu02] and [Leu04], the author proposed a similar concept to design optical networks to withstand error in demand forecasts. In [Leu02], the author employed a similar methodology as in [Gea01] to compare two design schemes based on different

restoration schemes. The aim was to maximize the fraction of all actual demands for which it is feasible to both route and protect with the network capacity corresponding to the optimal design for the original forecast. It was claimed that both the span-restorable scheme and the path-protected scheme are equally robust to errors in the demand forecasts. It should be noted that the study only considered a fixed total traffic volume. The variations in demand only occur through the varying traffic distributions. In [Leu04], a span-restorable scheme is considered to design optical network assuming demand uncertainty. The methodology proposed integrates both the capacity design and consideration of all the “what-if” scenarios into a single “future-proofing” design. The objective was to design a current network that strictly serves and protects all demands in the original forecast but which has a minimum total cost of current outlays and expected future costs to adapt the initial capacity plan to suit additional future demands that may arise. The resulting designs contain sufficient initial excess capacity to minimize the expected value of future outlays to cope with the what-if scenarios represented in the set of demand scenarios.

In [Mau02], the traffic uncertainty was modelled by statistical models, in which the number of connections between node-pairs was statistically generated. The uncertainty about the traffic patterns was then taken into consideration with network capacity dimensioning. The aim was to design the network with minimized capacity while ensuring the network was robust enough to accommodate deviations of the actual traffic patterns from those predicted.

All the studies described above deal with network planning and dimensioning, and aim to design optical networks with minimum cost/capacity but with maximum capability to ensure robustness to future traffic uncertainties. All the studies take traffic uncertainties as one of the network design parameters, and the proposed dimensioning processes are carried out based on the actual traffic variations. They consider pre-defined network topologies and assume symmetric traffic. Each of the three authors has proposed a novel metric to characterise the demand distribution uncertainty compared with the original expected demands. However, all the studies assume static design of the optical network. Therefore, once the communication channels are set up between node-pairs, they are never torn down. The traffic

uncertainties occurring in the traffic matrix during the planning process are dealt with implementing extra capacity in the event of extrapolation from previous forecasts.

In contrast, in the studies presented in this thesis, the aim is to investigate the tolerance of well dimensioned networks in which lightpaths are set up and torn down automatically, in particular, to study the capability of the networks to handle dynamic and uncertain traffic pattern distributions; to quantify this capability (which we term traffic forecast tolerance); to find out the related factors in the network that influence the traffic forecast tolerance; and to investigate techniques to improve the network tolerance. Although a number of previously published studies are similar to this research, to the author's knowledge, there has been no work, to date, carried out on this specific research topic.

## **3.2 Simulation of traffic pattern variations**

In the complex business environment, there are many factors contributing to the dynamic nature of today's traffic in optical networks. The unpredictable variations in the traffic distribution are due to the new service uncertainty introduced by technology development, customer behaviour uncertainty introduced by tough competition, and network operators' system upgrading and maintenance.

### **3.2.1 Traffic distribution models**

In this section, a number of models that can be used to characterize the traffic distribution are discussed. These methods can be used to generate point-to-point traffic at any granularity in any network layer. Each model has its advantages and disadvantages.

#### **3.2.1.1 Kruithof model**

If the proportions of the total traffic volume that are originating and terminating at each node are available, the Kruithof Model can be used to distribute the traffic between network nodes [Kru37] [Bea88].

The iterative process in the Kruithof Model results in a uniform distribution according to the predefined traffic volumes at each node. The amount of traffic between any two

network nodes will be proportional to the product of the two relevant node weights, divided by the total network traffic volume.

#### **3.2.1.2 Gravity model**

The Gravity Model assumes that the traffic from one network node to another is inversely proportional to some power of the distance between the network nodes. Hence, a higher value of the power results in an increasing localising effect. The Gravity Model actually represents the fact that people are mostly likely to communicate with those physically nearby. The distance between the network nodes is usually the straight line distance rather than the physical telecom line distance. In [Leu02], Gravity Model was employed to generate random traffic distributions.

#### **3.2.1.3 Dwivedi & Wagner model**

In [Dwi00], a long-distance traffic model for three applications is proposed based on [Sin94]. The latter gave a combined formula which considers the population, the network node geographical distance, and the level of adoption of new telecommunication services.

The former distinguishes different types of services, the voice traffic, the transaction data traffic, and the Internet traffic with total population, network node physical distance, number of business employees, and the number of internet hosts in each network node.

In [Vau03], the Dwivedi & Wagner traffic distribution model was improved in that a technology advancement factor was taken into consideration for both transaction data and Internet data to increase the projection accuracy.

#### **3.2.1.4 Communities of interest model**

In some special cases, the information about popular traffic trends is available. Specific communities of interest between nodes or groups of nodes may be known in advance. Hence it is also important to account for the communities of interest. Examples might be the cases of China's northern coast to southern coast traffic and

US East to West Coast traffic. Groups of nodes in different geographical location tend to have much greater traffic volumes than elsewhere.

### **3.2.1.5 Geary model**

In [Gea01, Gea03], a generic method is employed to generate a variety of different traffic distributions according to the many factors discussed above. The method can generate the aggregate of most traffic types, such as hub/adjacent/uniform traffic patterns using node weight, gravity model, and community of interests. Furthermore, the method can be used to generate random traffic patterns in addition, to test different network designs in terms of robustness.

### **3.2.1.6 Uniform/Adjacent/Hub model**

A uniform distribution of the traffic can be generated with the Kruithof Model. Besides the uniform traffic pattern, however, there exist two other main traffic patterns, i.e. adjacent and hub traffic patterns.

A substantial amount of traffic between neighbouring nodes may be resulting from the physical network topology. In the case of SDH rings, traffic is dropped at multiple nodes along the rim of the ring. The optical layer can be regarded as a set of lightpaths, forming a ring. To characterize such traffic, additional lightpath requests between adjacent nodes can be included as a defined proportion of the total traffic.

Hub traffic patterns describe a network node with greater importance than other nodes. It is the source and sink of more traffic than any other network node. An example in the UK network would be London, which is the capital city node or can be regarded as the international gateway node. This node, usually termed the hub node, may exchange traffic with all other nodes in the network. The addition of hub traffic to a traffic pattern sometimes provides a more realistic model of the network traffic.

Therefore in real traffic planning, traffic patterns are modelled as the combination of the three types with pre-defined traffic amount for each pattern. A typical ratio might be 70%, 10%, 20% for uniform traffic, adjacent traffic, and hub traffic respectively. The adjacent traffic becomes less important with the data traffic dominating the

network in the future. The Geary model generates three types of traffic respectively and combines the amount of each traffic pattern type as the total traffic volume.

### 3.2.2 Novel dynamic traffic distribution model

It should be noted that with the changes in the user behaviour and development of technology and applications, some of the key features of the traffic models may not be appropriate to characterize the data traffic in future optical core networks. The models which consider physical distance may no longer be a good assumption. In addition, data traffic will become less closely related with population in the future, hence the localising factors are becoming less important and the adjacent traffic volume is reduced. Furthermore, the traditional assumption in optical transport networks that the wavelength traffic is bi-directional can be questioned. It is assumed that the dimensioning of the capacity should be symmetric for bi-directional traffic, whereas the actual traffic that the network will be required to carry in the future may not necessarily be symmetric. The traffic may well exhibit non-uniform and asymmetric patterns.

Most importantly, static wavelength-routed optical networks are considered in most of the network planning and dimensioning studies that take into account future traffic uncertainties. As discussed in Section 2.4.4, future optical network will evolve to become dynamic wavelength-switched, optical burst switched, and, ultimately, optical packet switched networks. The static wavelength-routed optical network will become dynamic wavelength-routed optical network. In such networks, the communication channels are set up according to lightpath request arrivals, and the channels are then torn down when the transmission is completed. The fundamental difference between the two optical network architectures is that with the static wavelength-routed optical network, it is assumed that the lightpaths will never be torn down once set up, the traffic uncertainties relate to where and when future new lightpaths might be requested.

A novel traffic distribution model is presented here to characterize the dynamic nature of the traffic patterns in the dynamic wavelength-routed optical networks. It has the following advantages:



1. The model generates many different types of traffic patterns with the same total traffic volume.
2. The degree of the traffic pattern variation from the uniform traffic pattern can be easily controlled by adjusting one parameter.
3. The model generates both non-uniform and asymmetric traffic patterns.
4. The model can describe some of the extreme cases of the traffic patterns.
5. The model can be further employed to carry out analytical calculations.

The model is based primarily on a Poisson distribution with random variations generated by a uniform distribution. It has been clearly pointed out in Section 2.6.2.1 that the Poisson distribution might not be appropriate to use. In addition, it was argued in the earliest study of this topic in [Pax95] followed by many other studies that the lightpath request arrivals to be modelled as Poisson processes tend to deviate from actual Internet traffic, in which self-similar traffic with long-range dependence will become dominant in the future. It was shown that the Poisson model seriously underestimate the burstiness of TCP traffic over a wide range of time scales.

However, the most recent studies [Kar04A] [Kar04B] [Cao01] show that the packet arrivals of Internet traffic appear to be in agreement with the Poisson assumption in the core networks, which is obviously contradictory to the widely accepted long-range dependence nature of Internet traffic. In [Cao01], it is pointed that as the rate of new TCP connections increases, the arrival processes (packet and connection) tend locally toward Poisson, the time series variables (packet and connection) tend locally toward Poisson, and the time series variables (packet size, transferred file sizes, and connection round-trip times) tend locally toward independent variables. In [Kar04B], it is further suggested that the large increase of the network link speed and the number of Internet-hosts are reasons for the approximation of Poisson distributions becoming viable again with Internet core traffic. In addition, it is pointed out that the Internet TCP packet arrivals appear Poisson at sub-second time scales, Internet traffic appears nonstationary at multi-second time scales, and Internet traffic exhibits long-range dependence at scales of seconds and above.

Despite the discrepancies in these traffic model studies, the novel traffic model proposed here is based on the Poisson distribution simply because Poisson distribution has sufficient theoretical support to carry out further analytical calculations to prove the accuracy of the simulation result, whereas the long-range dependence analysis is hindered by the difficulty of actually identifying dependence and estimating its parameters unambiguously. To the knowledge of the author, up to the time of writing this thesis, there is a lack of theoretical support to accurately describe the long-range dependence nature of self-similar traffic.

The total traffic load is  $N(N-1)\rho_u$ , where  $N$  is the number of network nodes in the network, and  $\rho_u$  is the offered load per node-pair in the uniform traffic case, expressed as a fraction of one lightpath capacity.  $\rho_{ij}$  stands for the traffic load from node  $i$  to node  $j$  in the non-uniform traffic case. Between each node-pair, the lightpath request inter-arrival period is a Poisson-distributed random variable with a mean value  $\mu_u$  in the uniform traffic case, and the lightpath holding time,  $t_u$ , is an exponentially distributed variable. Traffic matrices were generated by the equation:

$$\rho'_{ij} = \frac{t_u}{\mu_u + (2X - 1)\sigma} \quad (3.1)$$

where  $X$  is a uniformly distributed random value between 0.0 and 1.0, and  $\sigma$  is termed the non-uniformity factor which controls the degree of uncertainty in the traffic request inter-arrival period.

The sum of the traffic load for each node-pair gives the total traffic volume. In practice, there will be discrepancies between the total traffic volume in the uniform case and the randomly generated total traffic volume, which will contribute to the differences in the performance of the network. To eliminate this effect, the total network load in each non-uniform traffic case is set exactly equal to that of the uniform loading,  $N(N-1)\rho_u$ , so that fair comparisons can be carried out. Hence, the loads for each non-uniform traffic case are scaled by a factor,  $\beta$ , ensuring that the randomly generated total traffic volume is the same as the original uniform traffic total load, given by

$$\beta = \frac{\sum_{i,j=0}^{N-1} \rho_{ij}}{N(N-1)\rho_u} \quad (3.2)$$

so that the actual loads between nodes  $i$  and  $j$  are given by

$$\rho_{ij} = \frac{\rho_{ij}}{\beta} \quad (3.3)$$

The traffic model generates the same total offered traffic load independently of the value of both the non-uniformity and the asymmetry. The traffic between node  $i$  to node  $j$  and node  $j$  to node  $i$  are treated independently, hence leading to asymmetric traffic volumes, as  $\rho_{ij}$  is not necessarily equal to  $\rho_{ji}$ .

The non-uniformity factor is chosen to adjust the variation from uniform traffic inter-arrival time period. A value of the non-uniformity factor,  $\sigma$ , between 0 and  $\mu_u$  is chosen. When the non-uniformity factor  $\sigma = 0$ ,  $\rho_{ij} = \frac{t_u}{\mu_u}$  becomes the uniform load  $\rho_u$ . According to the formulae 3.1, 3.2 and 3.3, the range of  $\rho_{ij}$  can be estimated as below,

$$\begin{aligned} \rho_{ij} &= \frac{t_u}{\mu_u + (2X-1)\sigma}, (0 \leq X \leq 1; 0 \leq \sigma \leq \mu_u) \\ \Rightarrow \frac{t_u}{2\mu_u} &\leq \rho_{ij} < \alpha, (\alpha \rightarrow \infty) \\ \Rightarrow \frac{t_u}{2\mu_u\beta} &\leq \rho_{ij} < \frac{\alpha}{\beta} \\ \Rightarrow \frac{t_u}{2\mu_u\beta} &\leq \rho_{ij} < N(N-1)\rho_u \end{aligned} \quad (3.4)$$

This range represents the extreme cases of the traffic patterns. It should be noted that when  $\rho_{ij}$  becomes a very large number  $\alpha$ , the scaling factor  $\beta$  will be very large too. Hence the final range of  $\rho_{ij}$  would be  $0 < \rho_{ij} < N(N-1)\rho_u$ . The physical meaning when  $\rho_{ij} = 0$  is that there is no communications between node  $i$  and node  $j$ . On the contrary, when  $\rho_{ij}$  is near  $N(N-1)\rho_u$ , the traffic between node  $i$  and  $j$  makes up the vast majority of the total traffic in the whole network. The range of  $\rho_{ij}$  is dependent on how  $\sigma$  is chosen. In this way, the degree of uncertainty can be easily

controlled by the non-uniformity factor. The model can be used to simulate the dynamic nature of future unpredictable traffic patterns.

It can be seen that the traffic model can be used not only to generate non-uniform traffic patterns, but also asymmetric traffic patterns and also some of the extreme traffic pattern scenarios. Wavelength-routed optical networks can be tested with the dynamic traffic model so that the network performance under different traffic patterns at different non-uniformity levels can be investigated. The performance of the network for a range of traffic patterns will determine the traffic forecast tolerance. A large number of traffic patterns can be randomly generated at each non-uniformity level, as a percentage of  $\mu_{ij}$ , to achieve this.

Fig.3.1 shows the performance of the NSFNET network with randomly generated traffic patterns at different non-uniformity levels. In this case, the traffic non-uniformity factor,  $\sigma$ , was increased incrementally from 0 to 0.5. For each value of the non-uniformity factor, 25 simulations were carried out, each with a randomly generated traffic pattern, allowing statistical distributions of the lightpath request blocking probabilities to be calculated.

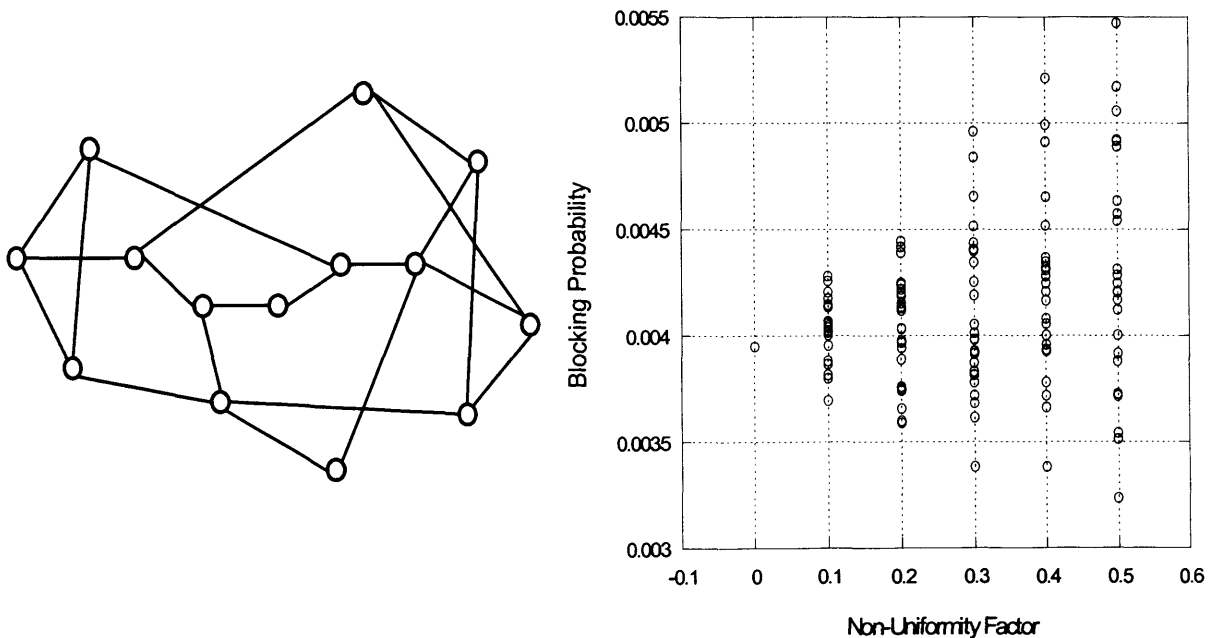


Figure 3.1 – Left: NSFTNET; right: lightpath request blocking probability versus non-uniformity factor for NSFNET (25 traffic patterns for each value of non-uniformity factor)

A dynamic RWA algorithm employing alternate routing with first fit wavelength allocation was used to obtain these results. 16 wavelengths per fibre were assumed, and no wavelength conversion was used (for this and all other studies described in this chapter). The total traffic load was equal to  $N(N-1)\rho_u = 140$  Erlangs. Between each node-pair, the lightpath request inter-arrival period was a Poisson distributed random variable with a mean value  $\mu_{ij} = 1.3$  in the uniform case. For the sake of simplicity, the lightpath holding time was an exponentially distributed variable with mean value  $t_{ij} = 1.0$  in all cases considered. The non-uniformity factors of 7%, 15%, 23%, 30%, and 38% of  $\mu_{ij}$  were used to test the network tolerance with different unpredictable traffic patterns.

If a greater number of randomly generated traffic patterns are employed, a more accurate indication of the network performance will be obtained. As an example, Fig. 3.2 shows results of the NSFNET network simulations with 100 randomly generated traffic patterns for each non-uniformity parameter under the same conditions as above.

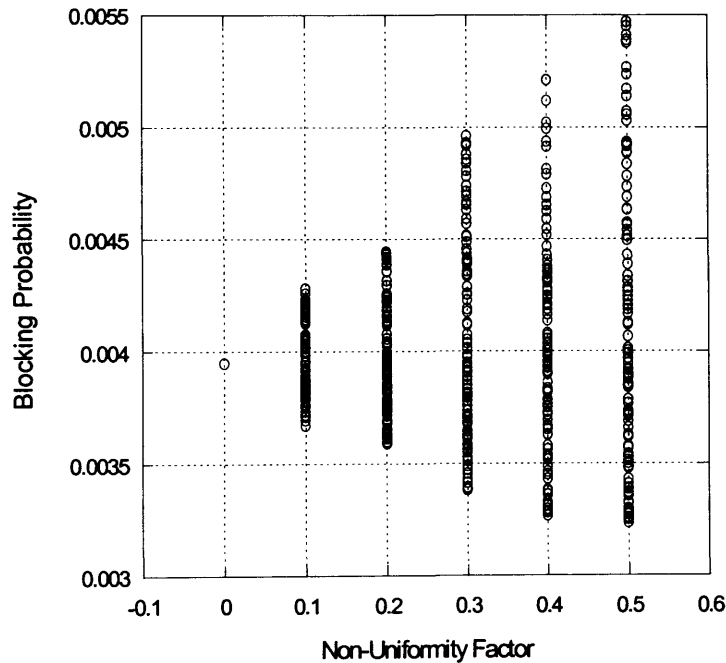


Figure 3.2 - Blocking performance versus non-uniformity factor for NSFNET (100 traffic patterns for each value of the non-uniformity factor)

It can be seen from Fig.3.2 that the range of the blocking probability distribution is approximately the same as the range of blocking probabilities in Fig.3.1, although in Fig.3.2, the gaps between the minimum value and maximum value are filled as more traffic patterns were tested on the network. The number of randomly generated traffic patterns required for each non-uniformity factor was varied, to find the optimum value which gives an accurate prediction of the blocking probability distribution. It was found empirically that for each non-uniformity factor, 20 to 30 patterns are sufficient to calculate the approximate blocking probability range. A larger number of randomly generated traffic patterns will fill in the gaps in the distribution of blocking probabilities and may give a more accurate result, however it is time-expensive to test the network with numerous traffic patterns.

### 3.2.3 RWA algorithm comparison

It is well known that the routing and wavelength assignment (RWA) algorithm plays a key role in the performance of optical networks. It is necessary to test the performance of different optical networks under different RWA algorithms. Since there are many RWA algorithms in the literature, it would be reasonable to compare different RWA algorithms first. In this section, a literature review of different RWA algorithms is given.

In dynamic optical networks, lightpaths between two nodes are established and released on demand in real time. Because of the requirement for real time RWA decisions, fast heuristic algorithms are required. Moreover, as future traffic demands are not known, the decisions taken in processing each lightpath request may not lead to an overall optimum configuration, unlike in the case of static optical networks, where analytical methods can be employed to reach the optimum solution.

A vast amount of work has been published on both heuristic and analytical RWA methods. In this section, heuristic algorithms solving dynamic RWA problems are discussed. The aim of heuristic RWA algorithms is to lower the blocking probability as much as possible. There are two categories of dynamic RWA algorithms. One considers the routing and wavelength allocation problems separately, the other

considers routing and wavelength allocation jointly. The vast majority of the heuristic algorithms are centralised, with a few distributed algorithms.

A widely used technique to solve the RWA problem involves dividing the problem into two parts: the routing part and wavelength assignment part. Normally, a list of possible routes between the source node and destination node is generated. The routes are usually put in an ascending order according to the physical length of each route. This route list can be fixed, dynamically generated or reordered according to the network state information. As for the wavelength assignment part, each wavelength is assigned a different number. A wavelength list is usually used. The list can be ordered arbitrarily or according to certain statistical parameters, e.g. wavelength utilisation.

It is natural to develop methods in which the route list is compiled first, and then a suitable wavelength from the wavelength list is chosen for each lightpath. A route would be picked first from the route list, and then the first wavelength in the wavelength list would be checked to determine whether it is available on all the physical links of the route. If not, the next wavelength in the list is checked, and the process repeated. If it is not possible to assign any wavelength to this route, then the next route from the list is considered. If, after all the routes have been considered, the connection could not be established, then the connection request is blocked.

On the contrary, an alternative method first selects a wavelength and then tries with all the routes from the list or dynamically calculated routes until it finds a route that can employ that wavelength. If the wavelength cannot be assigned to any routes, the next wavelength is selected exhaustively from the wavelength list until the connection can be established with a wavelength on an available route, otherwise the lightpath request has to be blocked.

Tab.3.1 shows a summary of the methods discussed here to solve the RWA problem given in [Zan00] [Mig02]. Most of the methods are suitable for both routing-first wavelength-second strategy and wavelength-first routing-second strategy, unless otherwise is stated in the table.

RWA Problem	Method
Routing	<ul style="list-style-type: none"> <li>• Fixed Routing (FR) [Bir95][Kar98][Xu00]</li> <li>• Fixed-Alternate Routing (FAR) [Bir95][Xu00][Ram95]</li> <li>• Adaptive routing: <ul style="list-style-type: none"> <li>Least Congested Path (LCP) [Cha94]</li> <li>Fixed-Paths Least-Congestion (FPLC) [Li99]</li> <li>Dynamic routing with neighbourhood information [Li99]</li> <li>Fabry-Asztalos et al. [Fab00]</li> <li>Spath [Spa00]</li> <li>Adaptive Unconstrained Routing (AUR) [Mok98] (only for wavelength first routing second)</li> </ul> </li> </ul>
Wavelength Assignment	<ul style="list-style-type: none"> <li>• RANDOM [Mok98] [Bir95] [Kar98] [Har97]</li> <li>• First Fit (FF) or Fixed [Fab00] [Ban96] [Ram95] [Mok98] [Bir95] [Kar98] [Har97]</li> <li>• Least Used (LU) or SPREAD [Mok98]</li> <li>• Most Used (MU) or PACK [Mok98] [Kar98] [Har97] [Sub97]</li> <li>• Birman and Kershenbaum [Bir95] (only for routing first and wavelength second)</li> <li>• Least Loaded (LL) [Kar98] (same as above)</li> <li>• Minimum Sum (MS) [Kar98] (same as above)</li> <li>• Minimum Product (MP) [Jeo96] (same as above)</li> <li>• Max Sum (<math>M \sum</math>) [Sub97] (same as above)</li> <li>• Relative Capacity Loss (RCL) [Zha98] (same as above)</li> <li>• Relative Least Influence (RLI) [Xu00] (same as above)</li> </ul>

Table 3.1 Summary of Heuristic Algorithms to Solve RWA Problems [Zan00]  
[Mig02]



Three types of routing have been proposed. They are fixed-routing, fixed-alternate routing, and adaptive routing. In fixed routing, a unique route is calculated for every node-pair. Fixed-routing has the advantage of fast execution speed since the route is calculated in advance. However, it also comes with high blocking probability due to its lack of flexibility. It is often referred to as shortest path routing. Fixed-alternate routing (FAR) is a variant of fixed-routing. In this scheme, a list of routes are calculated in advance and put in an ascending order according to the shortest distance or lowest number of hops. This offers more flexibility than the fixed-routing. Hence FAR offers an improved blocking probability performance. Adaptive routing is the most powerful amongst the three. It may have an ordered list of routes which is re-ordered from time to time according to the network status. LCP, FPLC, and Dynamic Routing with Neighbourhood Information are methods that use this technique. Or it may generate a new list of routes according to the network status every time it processes a lightpath request. Fabry-Asztalos [Fab00], Spath [Spa00], and Mokhtar [Mok98] use this technique.

LCP was proposed in [Cha94]. The method dynamically obtains the number of available wavelengths in the most congested physical link from each route. The route with the highest value of available wavelengths in the most congested link is then selected. Several criteria were used to break the tie. FPLC was proposed in [Li99]. The algorithm selects the route with the higher number of common available wavelengths in all the physical links. Dynamic Routing with Neighbourhood Information is a modified version of FPLC also proposed in [Li99]. The difference with FPLC is that the algorithm only checks the first  $k$  links of the route instead of the entire set of links in the route. It was reported that good results can be achieved with  $k=2$ . This algorithm obviously offers shorter execution time than the FPLC algorithm.

The Fabry-Asztalos algorithm was proposed in [Fab00], in which the routes are calculated for every node-pair dynamically. It executes the Dijkstra algorithm to find the shortest path with four different weight functions for the links. Two of them consider the number of available wavelengths while the other two consider distance. The Spath algorithm was proposed in [Spa00]. It uses a list of pre-calculated routes. If none of the listed routes can be used, a new route is dynamically found based on the network link utilisation. Mokhtar and Azizoglu proposed the AUR (Adaptive

Unconstrained Routing) methods, which considers the shortest physical path for each wavelength with the current network state information and finds the shortest one amongst all possible routes for the connection request.

As for the wavelength allocation, some algorithms consider the network status to determine the order in which wavelengths are searched. The RANDOM algorithm [Mok98] [Bir95] [Kar98] [Har97] selects wavelength randomly. The Fixed algorithm, also referred as the First-Fit algorithm [Fab00] [Ban96] [Ram95] [Mok98] [Bir95] [Kar98] [Har97], chooses the first-available lowest-numbered wavelength first. The LEAST USED (SPREAD) algorithm [Mok98] chooses the wavelengths that are least used in the network first. On the contrary, the MOST USED (PACK) algorithm [Mok98] [Kar98] [Har97] [Sub97] searches for the most used wavelength in the network. Some wavelength allocation algorithms consider both network status and the physical route that is already selected. Birman and Kershenbaum [Bir95] used First-Fit for one-hop routes and Last-Fit for routes with more than one hop. The Least Loaded algorithm [Kar98] chooses the lowest numbered wavelength that has the highest capacity in the route selected in multi-fibre networks. The Minimum Sum (MS) algorithm [Kar98] searches for the lowest numbered wavelength that has the lowest average utilisation as an alternative to the Least Loaded algorithm. The Minimum Product (MP) algorithm [Jeo96] searches for the lowest numbered wavelength which also has the minimum product in multi-fibre networks. The Max-Sum ( $M \sum$ ) algorithm [Sub97] searches for the wavelength that maximises the remaining path capacities after connection establishment. The Relative Capacity Loss (RCL) algorithm [Zha98] improves on the Max-Sum algorithm. RCL divides the capacity loss by the number of alternative wavelengths on which the connection could be established and the wavelength which minimises the relative capacity loss is chosen. The Relative Least Influence (RLI) algorithm [Xu00] considers the lowest numbered wavelength which meets certain criteria that result in the lowest influence on network resources.

Besides considering the RWA problems separately, some algorithms consider the selection of a physical route and a wavelength jointly. These algorithms have the advantage of lower blocking probability compared with the RWA algorithms

discussed previously. However, the lower blocking probability comes with higher computational complexity. These algorithms take a relatively longer time to find the route and wavelength for lightpath requests, which may affect the size of the network that can be considered. [Har97] proposed an algorithm that chooses the shortest route which has the highest number of available wavelengths, using one of the most utilised wavelengths in the network. Mokhtar and Azizoglu [Mok98] proposed the AUR-Exhaustive algorithm which dynamically searches for the shortest path from the temporary physical topology associated with each wavelength (sometimes referred to as the wavelength graph) at the arrival time of the lightpath request. Chen and Banerjee [Che96] proposed the same algorithm as [Mok98] but with a higher flexibility in the costs associated with the wavelength graph. Xu [Xu00] applied the above methods to multi-fibre networks with different tie break rules.

All the algorithms discussed above are for centralised optical network architectures. The entire network status information is usually known when considering RWA problems. A few distributed algorithms were proposed in literature. Compared with the centralised algorithms, they are more fault-tolerant. Moreover, the scalability problem with centralised system is naturally avoided in distributed systems. However, distributed algorithms are not the focus of this section.

It is very difficult to compare different RWA algorithms, since there are numerous parameters that influence the algorithm performance. The physical network topology, the network dimensioning, the use of wavelength conversion, and traffic characteristics are all influencing factors. After analysing different methods to solve the RWA problem, the algorithms are given in a contingent order below. The algorithms used for multi-fibre network are not included, as single-fibre networks are considered throughout the thesis. The algorithms are ordered according to the blocking probability performance, starting with the lowest blocking probability. On the contrary, their computational complexity is ordered starting with highest.

- AUR-Exhaustive [Mok98]
- FPLC-FF [Li99]
- FAR-RCL [Zha98]

- FAR-M  $\Sigma$  [Sub97]
- FAR-LL [Kar98]
- FAR-MU [Kar98] [Har97] [Sub97]
- FAR-FF [Bir95] [Kar98] [Ram95] [Ban96] [Fab00] [Har97]
- FAR-MP [Jeo96]
- FAR-RANDOM [Bir95] [Kar98]
- FR-FF [Bir95] [Kar98]
- FR-RANDOM [Bir95] [Kar98]

Among those RWA algorithms, Fixed-Routing can be regarded as a special case of Fixed-Alternate Routing when there is one and only one physical path in the route list. As discussed above, there are tradeoffs between blocking probability and computational complexity among RWA algorithms. It is also possible that in some cases the order may change. If the number of alternate routes is considered differently in different FAR algorithms, the order might change. Moreover, the list above is not complete, as some of the information required for comparisons is incomplete in the literature.

### **3.2.4 Network performance with RWA algorithms using the non-uniform traffic model**

It was important to test the dynamic traffic model with both lowest blocking performance but highest computational complexity RWA algorithm, i.e. AUR-Exhaustive, and the lowest computational complexity but highest blocking performance RWA algorithm, i.e. FR-FF. For further analytical comparisons, it was decided to choose an efficient RWA algorithm that has relatively low blocking probability and relatively low computational complexity. Hence, FAR-FF algorithm was chosen as it has been used widely. Alternate routes offer a certain degree of flexibility when choosing the lightpath, while the First-Fit wavelength allocation algorithm has been proved to be a fast and efficient algorithm to choose wavelengths in many papers.

Fig.3.3 shows the results of three different RWA algorithms on NSFNET under the same total traffic load of  $N(N-1)\rho_u = 140$  Erlangs at the same levels of traffic pattern non-uniformity. Fixed-Routing with First-Fit RWA algorithm was used first. It is the simplest algorithm, and the result can be used as a benchmark. FAR-FF RWA algorithm was then performed on NSFNET. The flexibility of one additional physical path is offered rather than the Fixed-Routing with only one physical route. Finally, the AUR-E algorithm was implemented. NSFNET was dimensioned as a single-fibre network (two fibres for every physical link, one for each direction) for reasons of simplicity, and equipped with 16 wavelengths for each fibre. Again, the mean inter-arrival period  $\mu_{ij} = 1.3$  was used in the uniform case. The lightpath holding time was an exponentially distributed variable with mean value  $t_{ij} = 1.0$  in all cases considered.  $\sigma$  was chosen at 7%, 15%, 23%, 30%, and 38% of  $\mu_{ij}$  to test the network tolerance under different unpredictable loading.

It can be seen from Fig.3.3 that FAR-FF with 2 alternate routes for each node-pair achieves far better performance than FR-FF with 1 route. AUR-E outperforms FAR-FF by a large margin in this case. However, the computational complexity of AUR-E is much higher than that of FAR-FF.

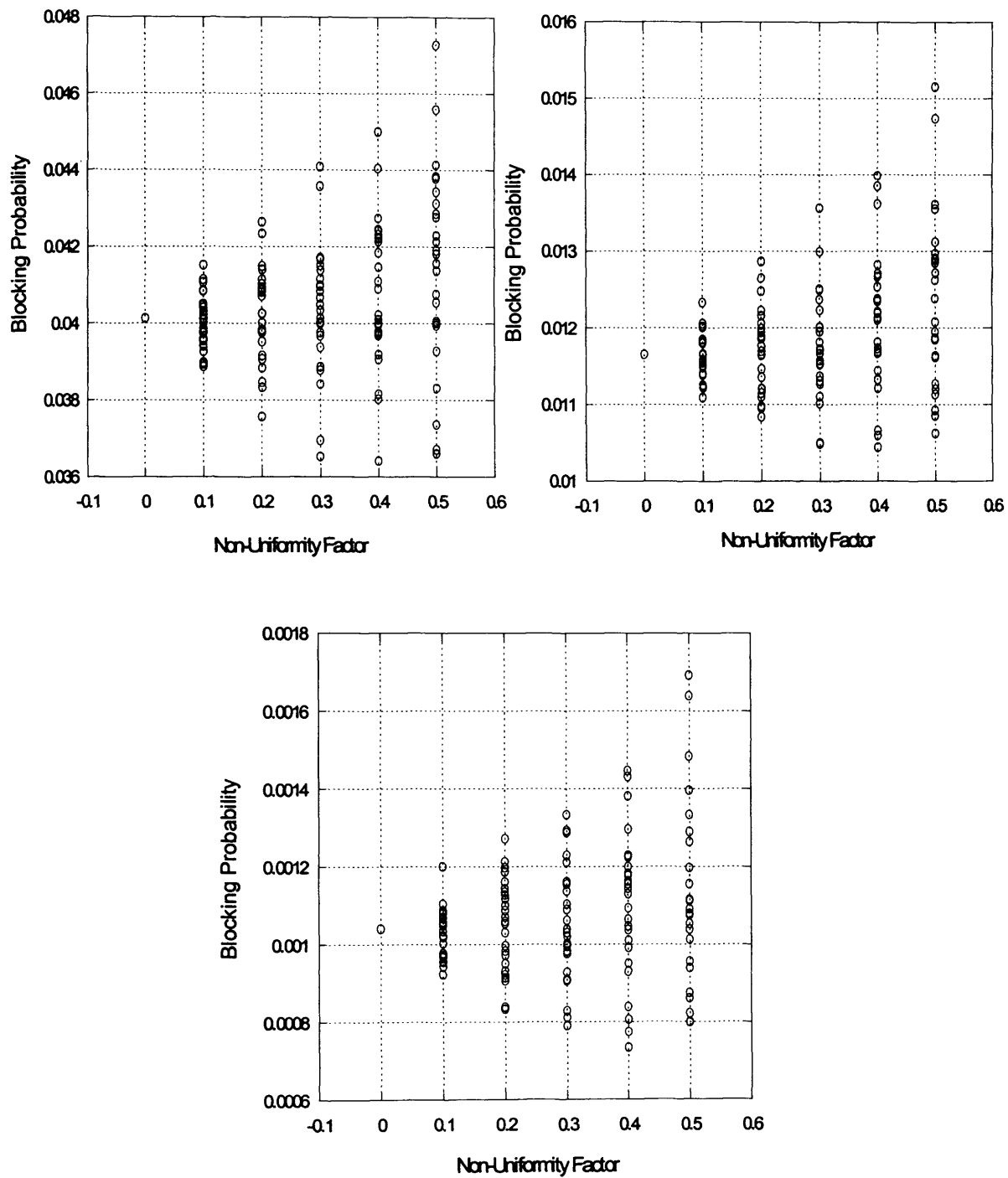


Figure 3.3 - Blocking probability versus non-uniformity factor of NSFNET with FR-FF, with FAR-FF, and with AUR-E routing and wavelength allocation algorithms (clockwise from top left)

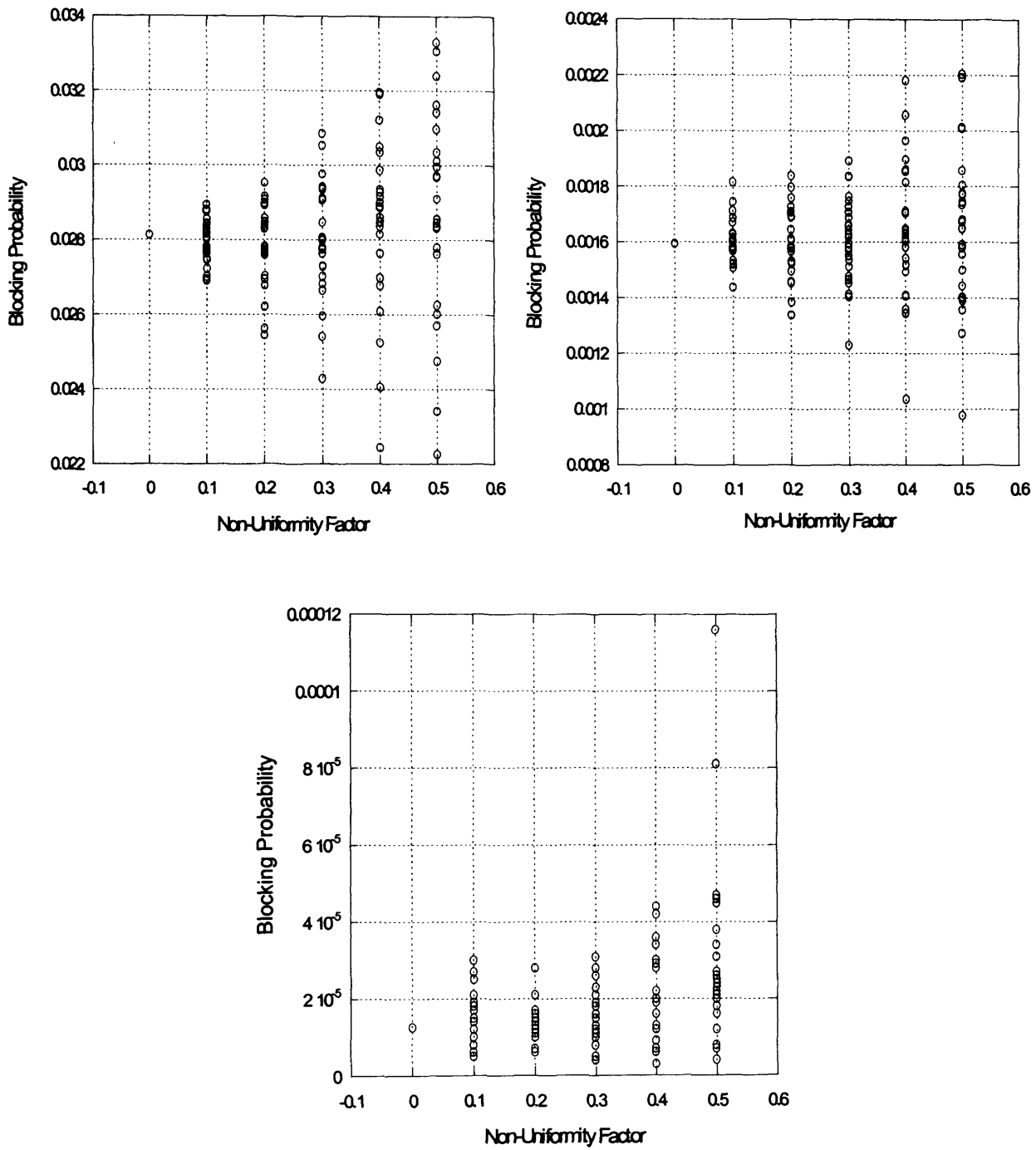


Figure 3.4 - Blocking probability versus non-uniformity factor of a randomly connected network with FR-FF, with FAR-FF, and with AUR-E routing and wavelength allocation algorithms (clockwise from top left)

A randomly connected network (RCN) with 15 nodes and 31 links was tested with the three same RWA algorithms. The network topology is shown in Fig.3.5. Each fibre was equipped with 16 wavelengths. The initial total traffic load to test the FR-FF and FAR-FF algorithms was  $N(N-1)\rho_u = 161.53$  Erlangs with mean inter-arrival period  $\mu_{ij} = 1.3$  and lightpath mean holding time  $t_{ij} = 1.0$  in all cases. The traffic non-uniformity factor was taken at 7%, 15%, 23%, 30%, and 38% of the mean inter-arrival period. 25 simulations were carried out for each non-uniformity factor, each simulation with 1 million traffic requests. However, with total traffic load of 161.53 Erlangs, the simulation with AUR-E algorithm resulted in no lightpath requests being blocked. Hence, the total traffic load was increased to  $N(N-1)\rho_u = 206.67$  Erlangs with mean inter-arrival period  $\mu_{ij} = 1.016$ . All other conditions were kept the same. Accordingly, the traffic non-uniformity factor was taken at 9.8%, 19.68%, 29.5%, 39.36%, and 49.2%. Interestingly, it can be seen that in Fig. 3.4 the blocking distribution is no longer symmetric. The three RWA algorithms give different blocking probabilities in ascending order: AUR-E, FAR-FF, and FR-FF.

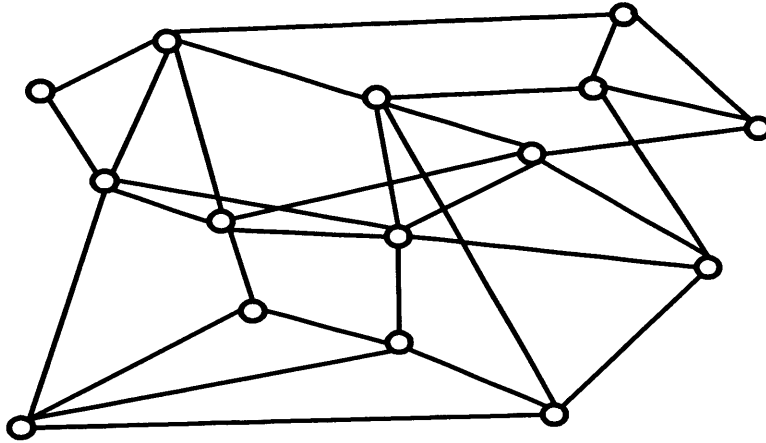


Figure 3.5 - Physical network topology of the randomly generated network



### 3.2.5 Network performance with various physical network topologies

Following the studies described in the previous section, it was next necessary to test different physical network topologies with the dynamic traffic model. Ring network topologies, mesh and practical network topologies, and randomly connected network topologies of different sizes were tested with the dynamic traffic model. As discussed in Section 3.2.2, 20 to 30 simulations would cover the blocking distribution range at different traffic non-uniformity degree. Hence 25 simulation runs were carried out for each non-uniformity factor in all cases. Furthermore, the lightpath holding time,  $t_u$ , was kept at the same, fixed value for all node pairs all cases for simplicity. The offered traffic load can be easily increased or decreased by adjusting the mean lightpath request inter-arrival period. The topologies, network dimensioning, and load conditions considered are summarised in Tab.3.2.

In particular, the notations in the table are described as:  $N$ , number of nodes;  $L$ , number of links;  $W$ , number of wavelengths per fibre;  $\sum_{i,j=0}^{i,j=N-1} \rho_{ij}$ , total offered load to network in Erlangs;  $\mu_u$ , mean traffic request inter-arrival period; %, non-uniformity factor in percentage of  $\mu_u$ ;  $RWA$ , routing and wavelength allocation algorithm;  $A$ , number of traffic request arrivals for each simulation run;  $R$ , figure number showing result.

The blocking probability performances for different physical network topologies under various load conditions are shown in figures with the non-uniformity factor.

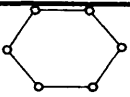
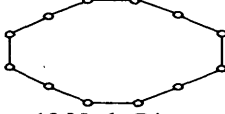
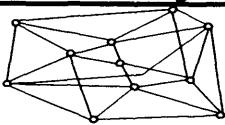
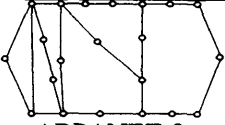
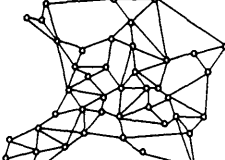
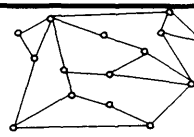
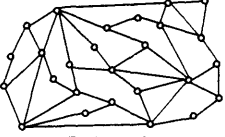
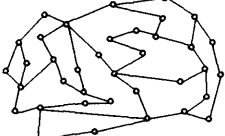
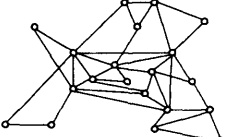
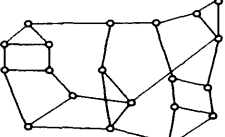
Network	$N$	$L$	$W$	$\sum_{i,j=0}^{i,j=N-1} \rho_{ij}$	$\mu_u$	%	RWA	$A$	$R$
 6 Node Ring	6	6	8	20	1.5	16.7% 33.4% 50.1%	AURE FARFF2 FRFF	$3 \cdot 10^5$	Fig.3.6
 12 Node Ring	12	12	16	57.4	2.3	16.7% 33.4% 50.1%	AURE FARFF2 FRFF	$6 \cdot 10^5$	Fig.3.7
 EUROCORE	11	25	8	84.6	1.3	16.7% 33.4% 50.1%	FARFF2 FRFF	$6 \cdot 10^5$	Fig.3.8
 ARPANET-2	21	26	16	84	5	16.7% 33.4% 50.1% 66.8%	FARFF2 FRFF	$1 \cdot 10^6$	Fig.3.9
 EUROLARGE	43	90	32	451.5	4	16.7% 33.4% 50.1% 66.8%	FARFF2 FRFF	$2 \cdot 10^6$	Fig.3.10
 RCN_1	15	22	8	42	5	16.7% 33.4% 50.1% 66.8% 83.5%	FARFF2 FRFF	$1 \cdot 10^6$	Fig.3.11
 RCN_2	26	45	16	130	5	16.7% 33.4% 50.1% 66.8% 83.5%	FARFF2 FRFF	$2 \cdot 10^6$	Fig.3.12
 RCN_3	37	47	32	242.2	5.5	25% 50% 75% 100%	FARFF2 FRFF	$2 \cdot 10^6$	Fig.3.13
 EON	20	39	64	844.4	0.45	25% 50% 75% 100%	FARFF3	$2 \cdot 10^6$	Fig.3.14
 ARPANET	20	31	128	1266.67	0.3	25% 50% 75% 100%	FARFF3	$2 \cdot 10^6$	Fig.3.15

Table 3.2 Summary for network topologies with dynamic traffic model

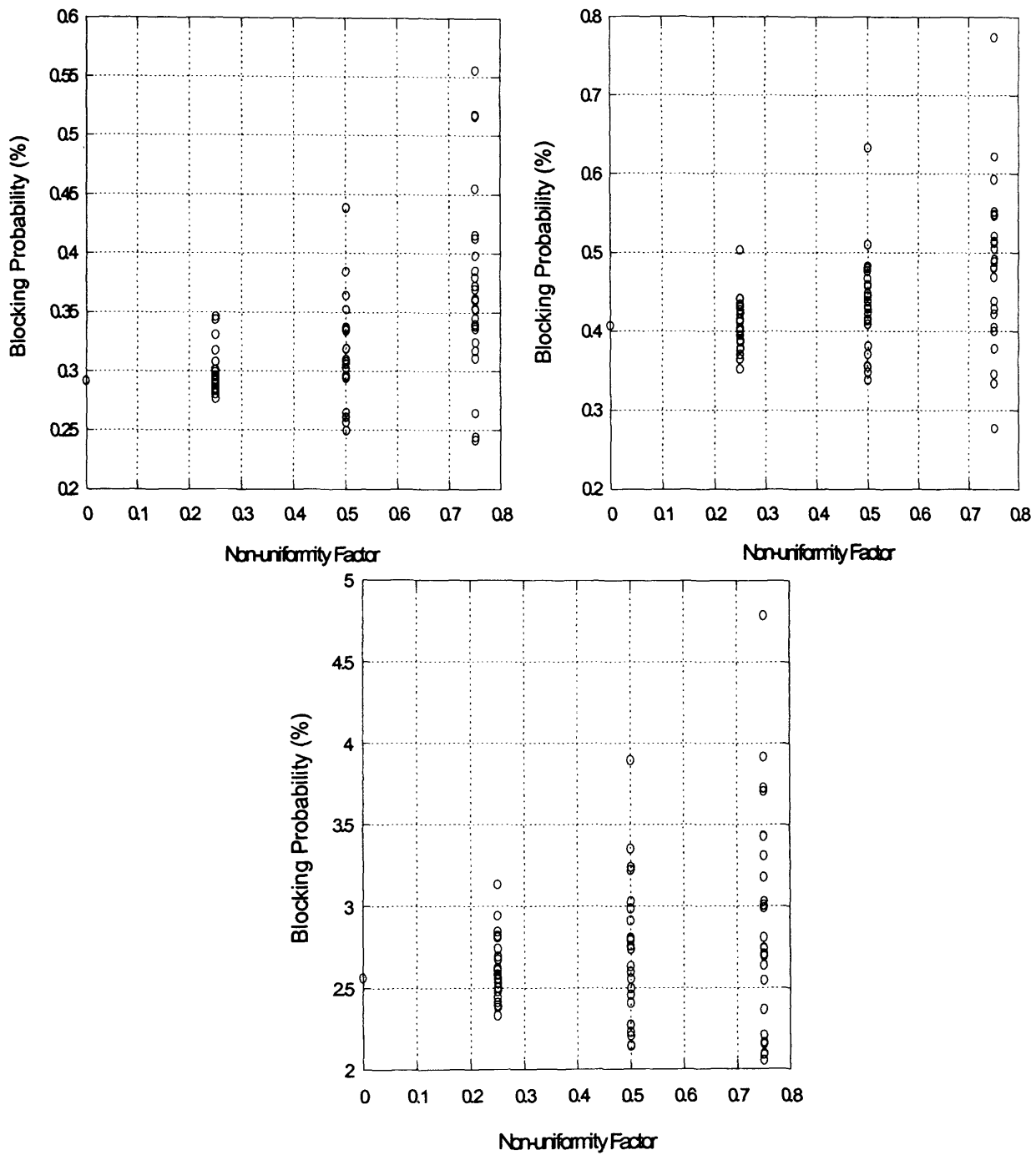


Figure 3.6 – Blocking probability of a 6-node-ring with AUR-E, FAR-FF, and FR-FF RWA algorithms under dynamic traffic model (clockwise from top left)

The 6-Node-Ring was equipped with 8 wavelengths per fibre and tested with a total traffic load of 20 Erlangs with mean traffic request inter-arrival period of 1.3 and mean request holding time 1.0. The non-uniformity factors were chosen to be 16.7%, 33.4%, and 50.1% of the mean request inter-arrival period. It can be seen from Fig.3.6 that AUR-E and FAR-FF with two routes for each node-pair outperformed FR-FF by a large margin. However, the performance difference between AUR-E and FAR-FF is not large. This is caused by the physical feature of ring topology. For each node-pair, there are only two physical paths to set up the lightpath. This limits the ability of AUR-E algorithm to optimise the routing of the lightpath between node-pairs.

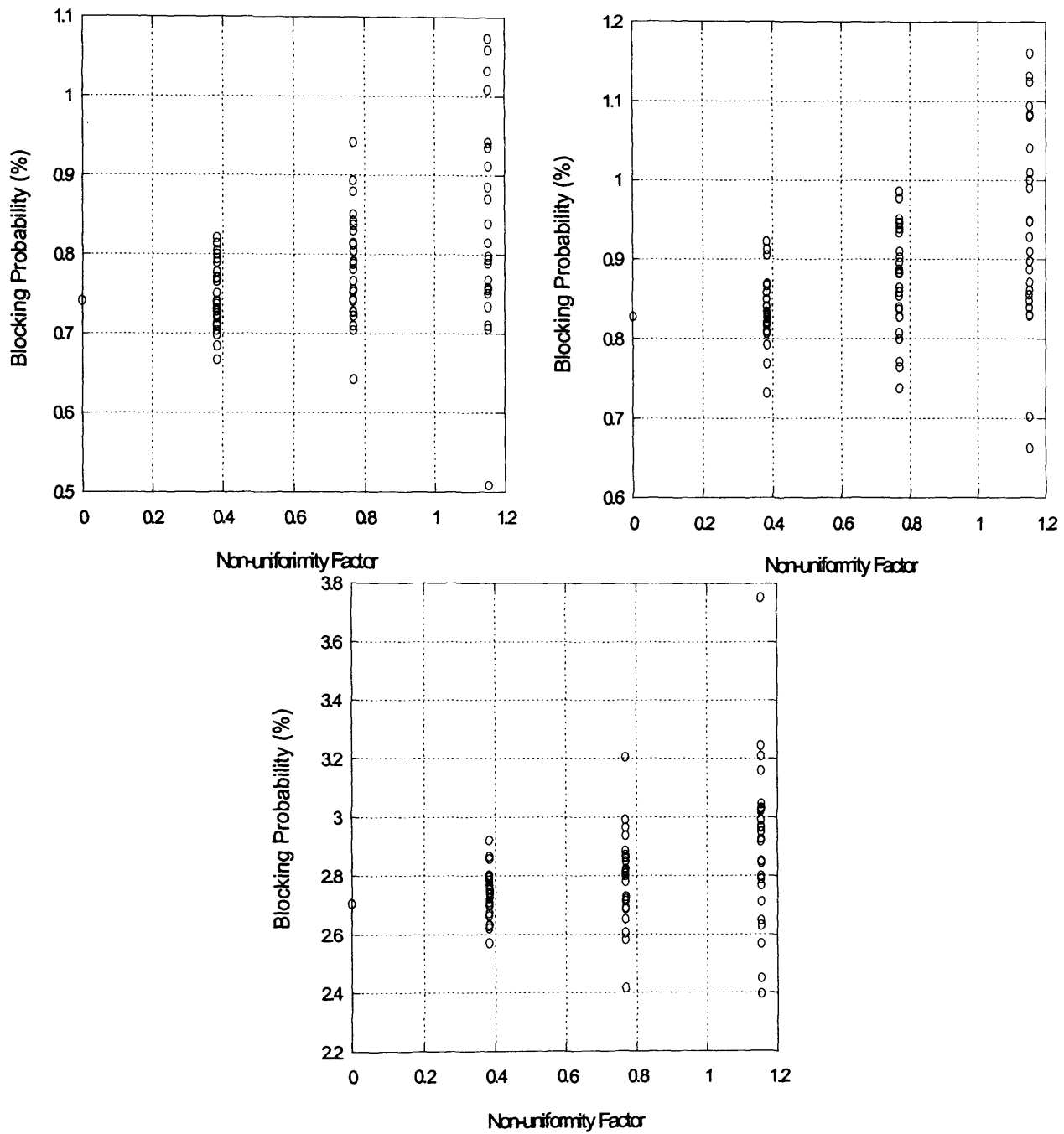


Figure 3.7 – Blocking probability of a 12-node-ring with AUR-E, FAR-FF, and FR-FF RWA algorithms under dynamic traffic model (clockwise from top left)

Fig.3.7 shows the network performance of the 12-Node-Ring, double the size of the 6-Node-Ring. The dimensioning is doubled such that each fibre is equipped with 16 wavelengths. The total traffic load is 57.4 Erlangs with mean traffic request inter-arrival of 2.3 and mean request holding time of 1.0. Similar results were obtained, in which AUR-E and FAR-FF with two routes for each node-pair significantly outperformed FR-FF. Again, the performance difference between AUR-E and FAR-FF was not large due to the topological nature of ring as discussed above.

Besides the ring network topologies, practical mesh networks have been tested. EUROCORE, ARPANET-2, and EUROLARGE topologies were tested with the dynamic traffic model, as they are examples of different sizes of practical networks. EUROCORE network has 11 nodes and 25 physical links; ARPANET-2 network has 21 nodes and 26 physical links, whereas EUROLARGE network has 43 nodes and 90 physical links.

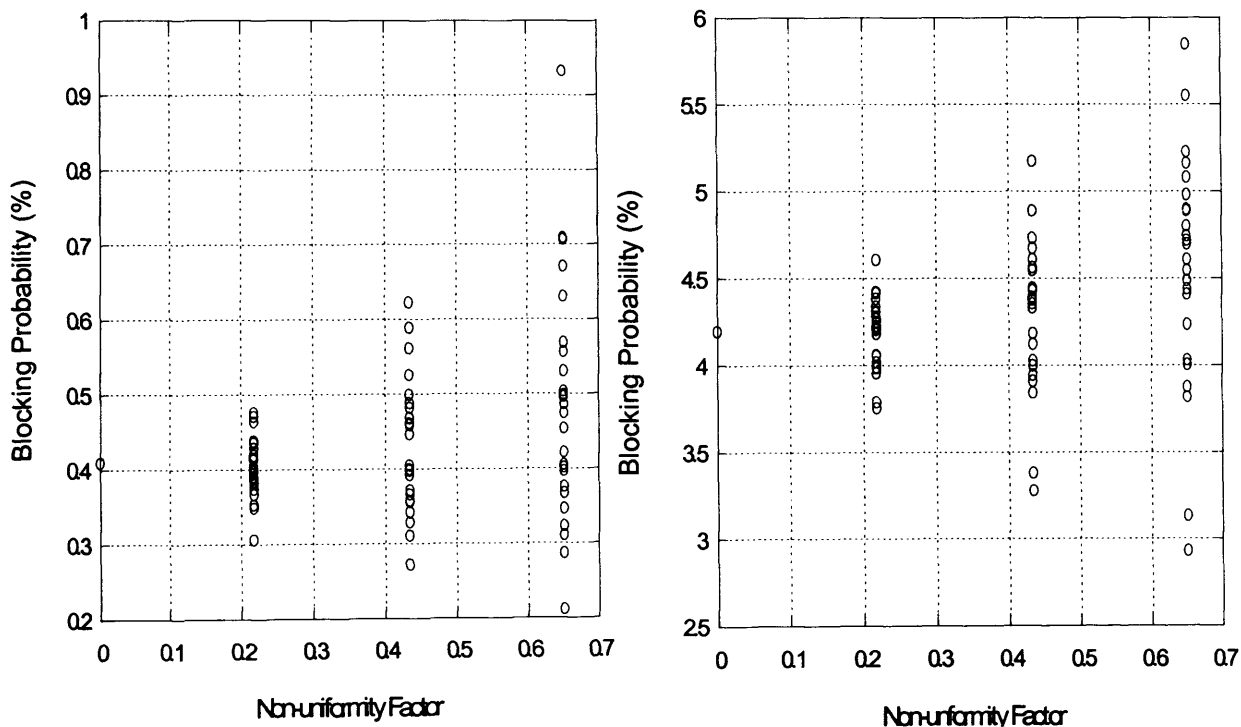


Figure 3.8 - Blocking probability versus non-uniformity factor for EUROCORE network with FAR-FF (left) and FR-FF (right)

The EUROCORE network was equipped with 8 wavelengths per fibre and tested with a total traffic load of 84.61 Erlangs. The mean traffic request inter-arrival time was 1.3 and the mean lightpath holding time was 1.0. FAR-FF outperformed FR-FF by an order of magnitude due to the additional physical route for each lightpath to choose from. The non-uniformity factor was chosen at 16.7%, 33.4%, and 50.1% of the mean inter-arrival period.

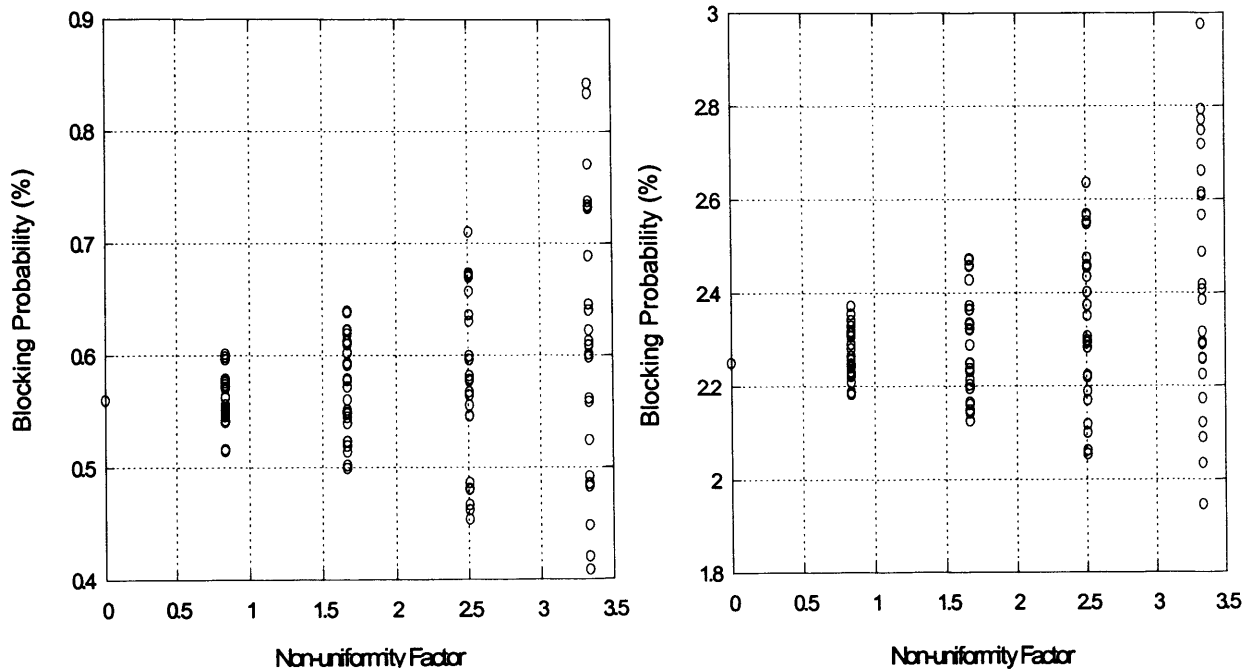


Figure 3.9 - Blocking probability versus non-uniformity factor for ARPANET-2 network with FAR-FF (left) and FR-FF (right)

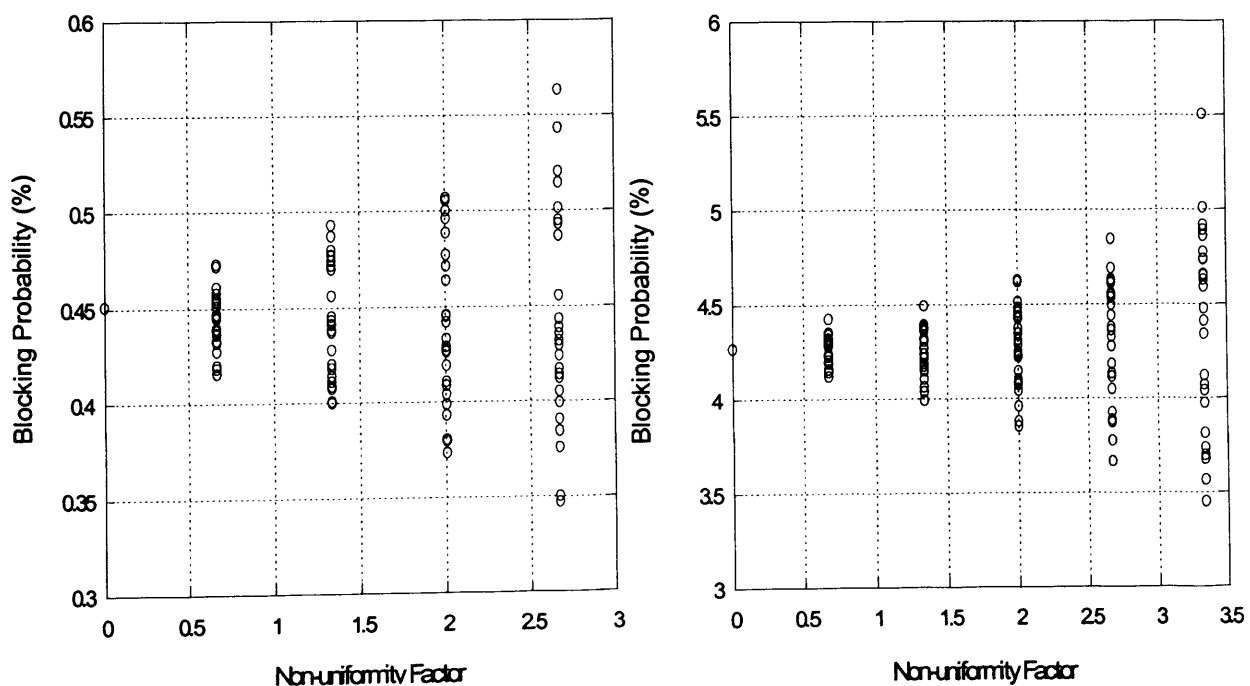


Figure 3.10 - Blocking probability versus non-uniformity factor for EUROLARGE network with FAR-FF (left) and FR-FF (right)

It can be seen in Fig.3.9 and Fig.3.10 that FAR-FF algorithm with 2 physical routes for each node-pair performed approximately 4 times better than FR-FF algorithm in ARPANET-2 network, whereas on EUROLARGE network FAR-FF outperformed FR-FF by nearly an order of magnitude. The dependence of the performance on the RWA algorithm used was therefore found to vary significantly due to the network topology.

Some randomly connected networks (RCN) were also tested with the dynamic traffic model. Three sizes of RCN were chosen with 15, 26, 37 network nodes and 22, 45, and 47 physical links respectively.

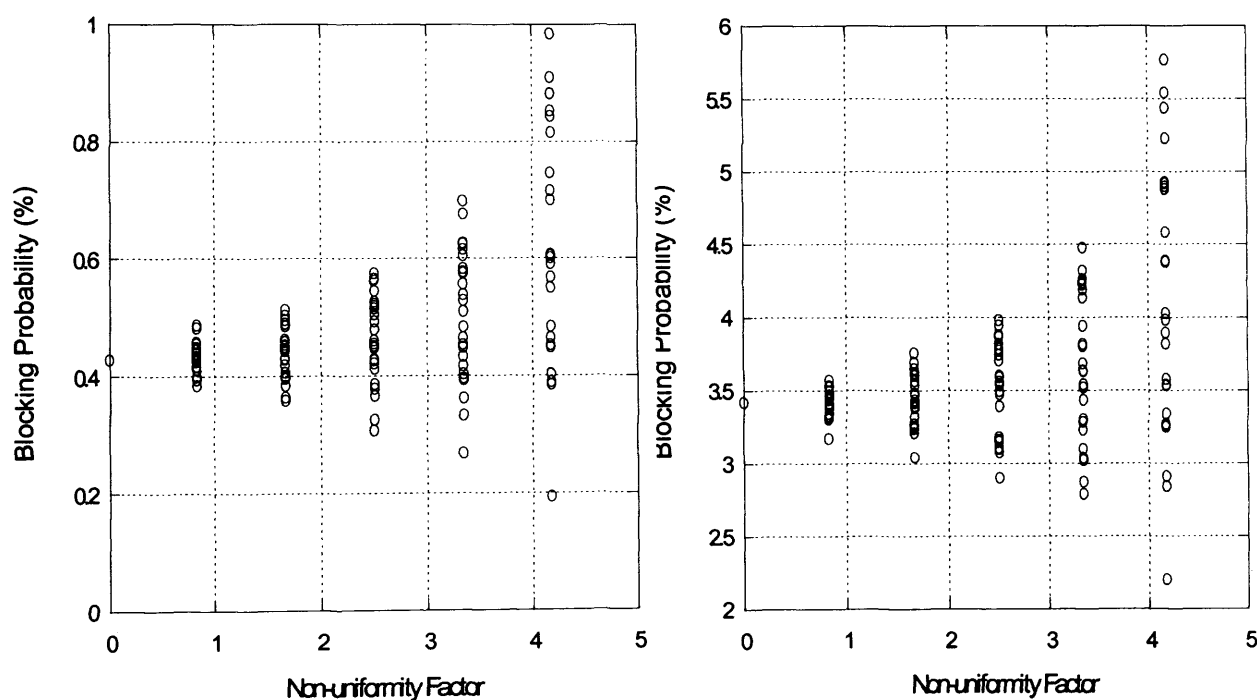


Figure 3.11 - Blocking probability versus non-uniformity factor for a RCN with 15 nodes and physical 22 links with FAR-FF (left) and FR-FF (right)



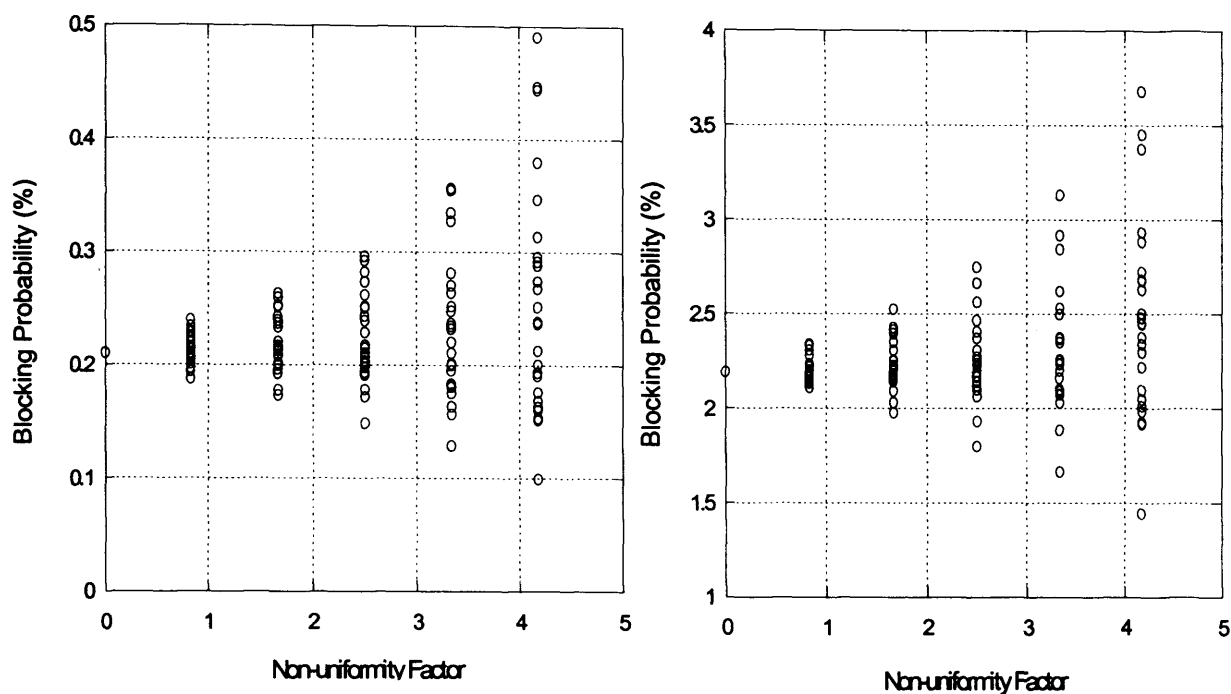


Figure 3.12 – Blocking probability versus non-uniformity factor for a RCN with 26 nodes and 45 physical links with FAR-FF (left) and FR-FF (right)

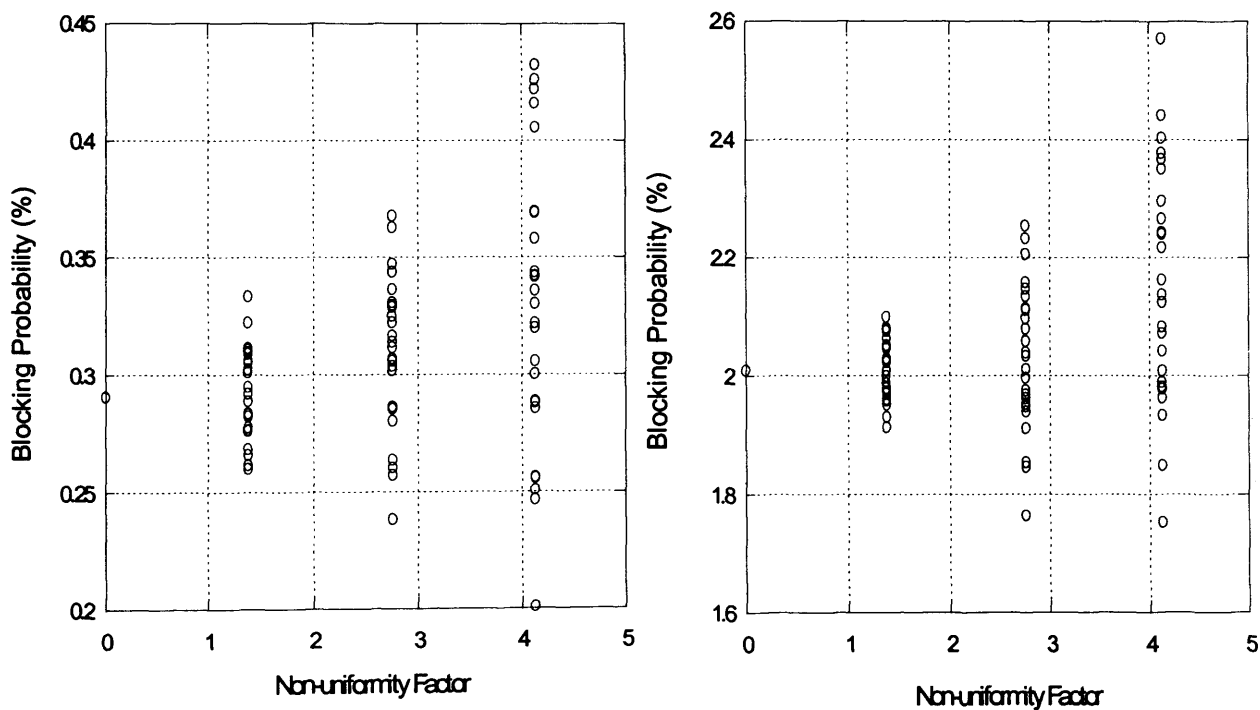


Figure 3.13 - Blocking probability versus non-uniformity factor for a RCN with 37 nodes and 47 physical links with FAR-FF (left) and FR-FF (right)

The RCNs were generated subject to the constraint that any two subsets of the network nodes were connected by at least two links. This is a fundamental requirement for network reliability, so that in the case of a single link failure, the network remains connected, and restoration lightpaths can be established along alternative physical paths. Therefore, a consequence is that the minimum number of fibres incoming and outgoing any node, referred to as the nodal degree  $\delta$ , is  $\delta_{\min} = 2$ . The ring network topology is considered as a special case, in which the number of nodes and the number of links are the same. Again, in the results of RCNs, the FAR-FF algorithm showed its advantage over the FR-FF algorithm.

### 3.2.6 Network performance under extreme traffic scenarios

The traffic model was also tested with different numbers of wavelengths. As discussed in section 3.2.2, the traffic model can describe some of the extreme cases of traffic scenarios, when the non-uniformity factor is chosen near the value of the traffic request mean inter-arrival period. Fig.3.14 and Fig.3.15 show the blocking performance of EON and ARPANET networks with FAR-FF RWA considering 3 alternate routes for each node-pair when the non-uniformity factor reaches the value of the traffic request mean inter-arrival period.

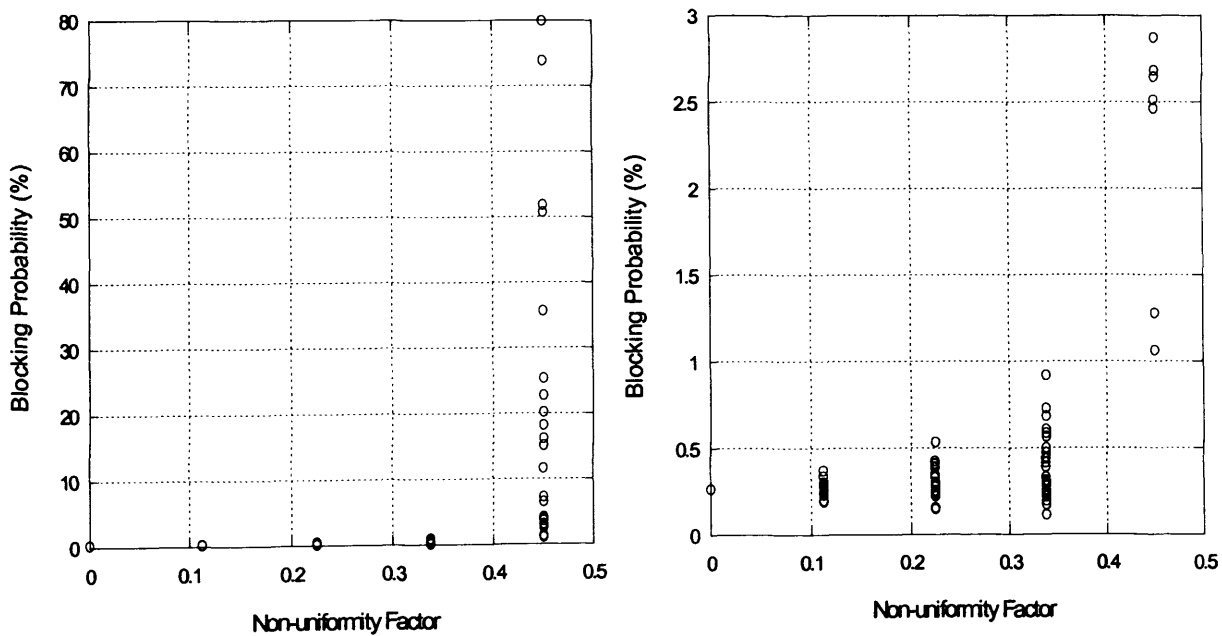


Figure 3.14 – Blocking probability versus non-uniformity factor of EON network with extreme traffic scenarios (right graph is a zoom-in of left graph)

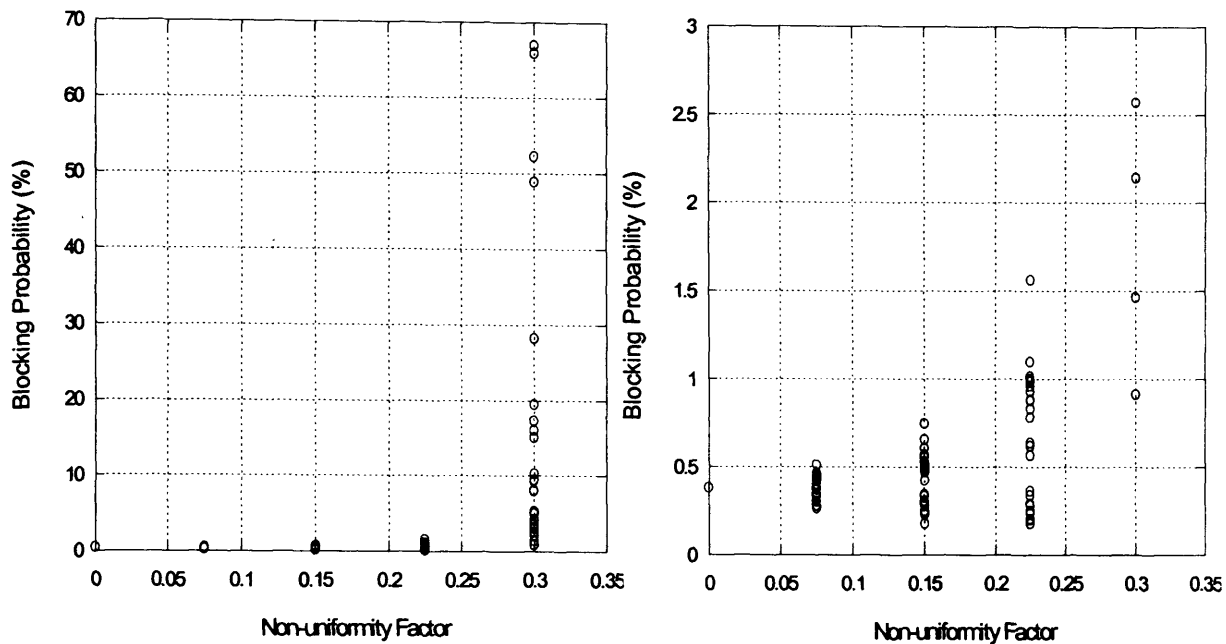


Figure 3.15 – Blocking probability versus non-uniformity factor of ARPANET network with extreme traffic scenarios (right graph is a zoom-in of left graph)

Both EON and ARPANET network were tested with the dynamic traffic model. EON network was equipped with 64 wavelengths per fibre and ARPANET network was equipped with 128 wavelengths per fibre. The plots on the right of both Fig.3.14 and Fig.3.15 show the details when the blocking probability is below 3%. These results also show that the results with large number of wavelengths are consistent with the results of lower number of wavelength. As the non-uniformity factor reaches 100% percent of mean traffic request inter-arrival period for both networks, the blocking probability distribution is no longer symmetrical. When the non-uniformity factor approaches the mean traffic request inter-arrival period, as discussed in section 3.2.2, some node-pairs may absorb the majority of the total offered load to the whole network. In the extreme case, one node-pair absorbs nearly 100% of the total network traffic, and the entire simulation involves finding an available wavelength along all the physical links of the routes between the source node and destination node of this specific node-pair to set up the required lightpaths. In this circumstance, the lightpath requests to this node-pair arrive much more frequently than to the other node-pairs, hence the network blocking probability becomes equal to the blocking probability of

this specific node-pair. The node-pair is usually able to serve only a small part of the total demand, and hence a large part of the demand is blocked due to the lack of resources for the node-pair. This is the reason why the blocking performance degrades when the non-uniformity equals the mean traffic request inter-arrival time. Each node-pair has an equal probability of becoming the one that bears the majority of the whole load offered to the network.

For both of these network topologies, the FAR-FF algorithm with 3 alternate routes for each node-pair was employed. Hence the possibility to set up a lightpath for each node-pair is higher than FAR-FF algorithm with only 2 alternate routes. However, this depends on the physical layout of the network topology. If most of the network nodes have a nodal degree  $\delta = 2$ , (e.g. in the case of the ring networks), which means only two disjoint routes can be found for most of the node-pairs, a large performance difference will not exist between the two, since the possibility of finding a third disjoint-link path for any node-pair is low.

### 3.3 Quantification and comparison of traffic forecast tolerance

The blocking performance of different network topologies under various traffic situations are shown and discussed in Section. 3.2. In this section, the quantification of the traffic forecast tolerance is discussed and a formula proposed for this purpose.

#### 3.3.1 Quantification of traffic forecast tolerance

In all the results of network performance in section 3.2, it can be seen that the spread in the blocking probabilities increases with increasing non-uniformity factor,  $\sigma$ . The non-uniformity factor stands for the degree of variation between the uniform traffic loading and the considered non-uniform loading. The wider the spread of blocking probabilities with non-uniform loading, the worse the performance of the network; the network has a lower robustness to the unknown future traffic pattern variations. The robustness of any network to accommodate the unpredictable traffic pattern variations is defined as the traffic forecast tolerance (TFT).

The width of the blocking probability spread can be described by the standard deviation. Therefore, the traffic forecast tolerance can be quantified by the increase in the standard deviation of blocking probability values with increasing load non-uniformity.  $N$  is the number of randomly generated traffic patterns.  $\sigma$  is the non-uniformity factor, which is chosen as a certain percentage of the mean lightpath request inter-arrival time.  $\sigma_a$  represents the standard deviation of the blocking probabilities with the given non-uniformity factor,  $\sigma$ . The equation below is the analytical expression quantifying traffic forecast tolerance:

$$\sigma_a = \sqrt{\frac{1}{N} \sum_{i=1}^N (BP_i - \overline{BP})^2} \quad (3.5)$$

$BP_i$  is the blocking probability under  $i$ th randomly generated traffic pattern, whereas

$$\overline{BP} = \frac{1}{N} \sum_{i=1}^N BP_i \quad (3.6)$$

is the average blocking probability of all traffic patterns with non-uniformity factor  $\sigma$ .

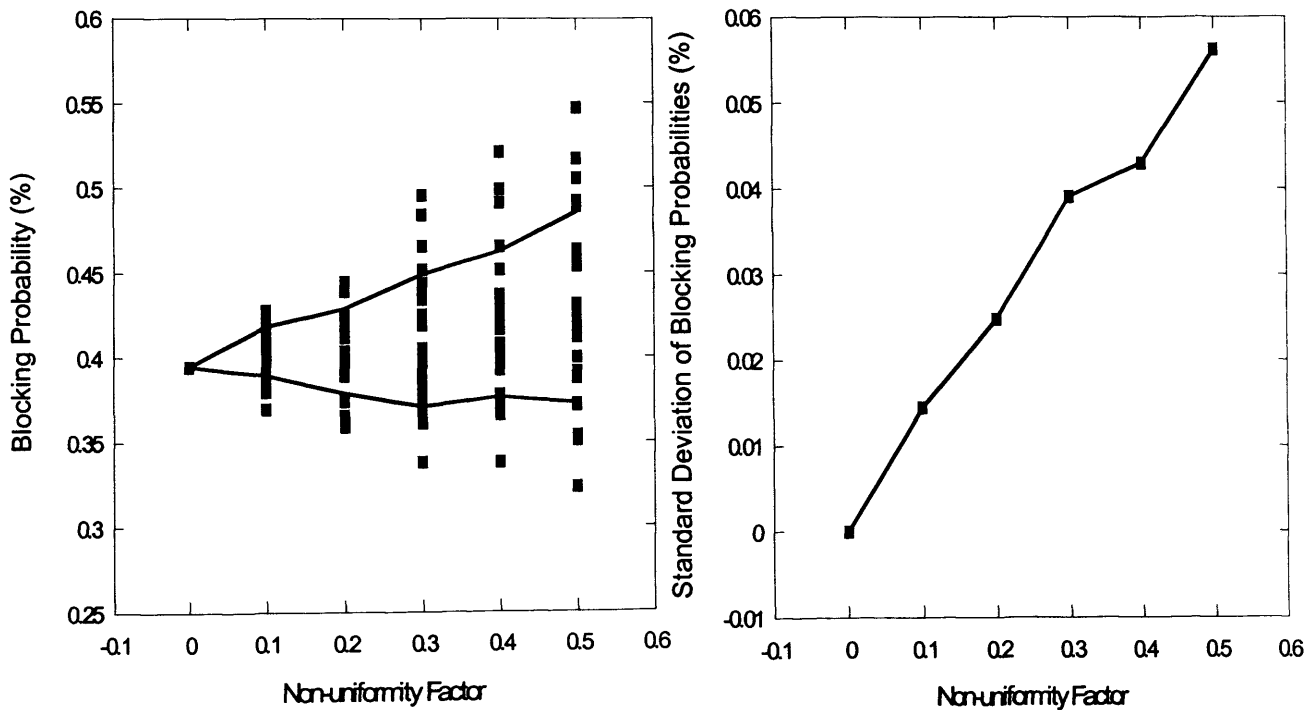


Figure 3.16 - Blocking Performance of NSFNET with Non-uniformity (left) Blocking Probabilities Standard Deviation with Non-uniformity (right)

Fig.3.16 shows the blocking performance of NSFNET with calculated values of standard deviation. The solid line in Fig.3.16 (left) is the mean blocking probability plus/minus the standard deviation of all the blocking probabilities. By carrying out multiple simulations to calculate the blocking probabilities, the network tolerance can be easily obtained. It can be seen from Fig.3.16 (right) that the standard deviation increases with the increasing non-uniformity factor. Hence the network traffic forecast tolerance is quantified by the increase in the standard deviation of the blocking probability distributions with increasing traffic non-uniformity. Thus the traffic forecast tolerance of NSFNET with 16 wavelengths per fibre and FAR-FF RWA algorithm under 140 Erlangs of total traffic load is quantified.

Networks that have a lower standard deviation of blocking probability with increasing traffic non-uniformity are those exhibiting higher tolerance to unpredictable traffic pattern variations, or traffic forecast tolerance.

### 3.3.2 Comparison of quantified TFT for different networks

From Section 3.2, it can be seen that different networks have different traffic forecast tolerances. The physical topology of the network, the network dimensioning, the RWA algorithm, and the traffic load can influence the network tolerance in different ways. Thus it is important to design networks with the capability to handle future unpredictable traffic pattern variations. While optimizing the network dimensioning in order to make networks sufficiently robust to accommodate unpredictable traffic patterns may be an important task, comparing traffic forecast tolerance is another important application when analyzing networks with the same dimensioning and RWA algorithm, but with slightly different physical topologies.

Fig.3.17 and Fig.3.18 show the blocking performance and traffic forecast tolerance of networks with similar physical topologies under the same network dimensioning, with same RWA algorithm, and with same total traffic load. To generate these network topologies, a topology described in the literature was used as a starting point, and the location of one physical link was changed at random.

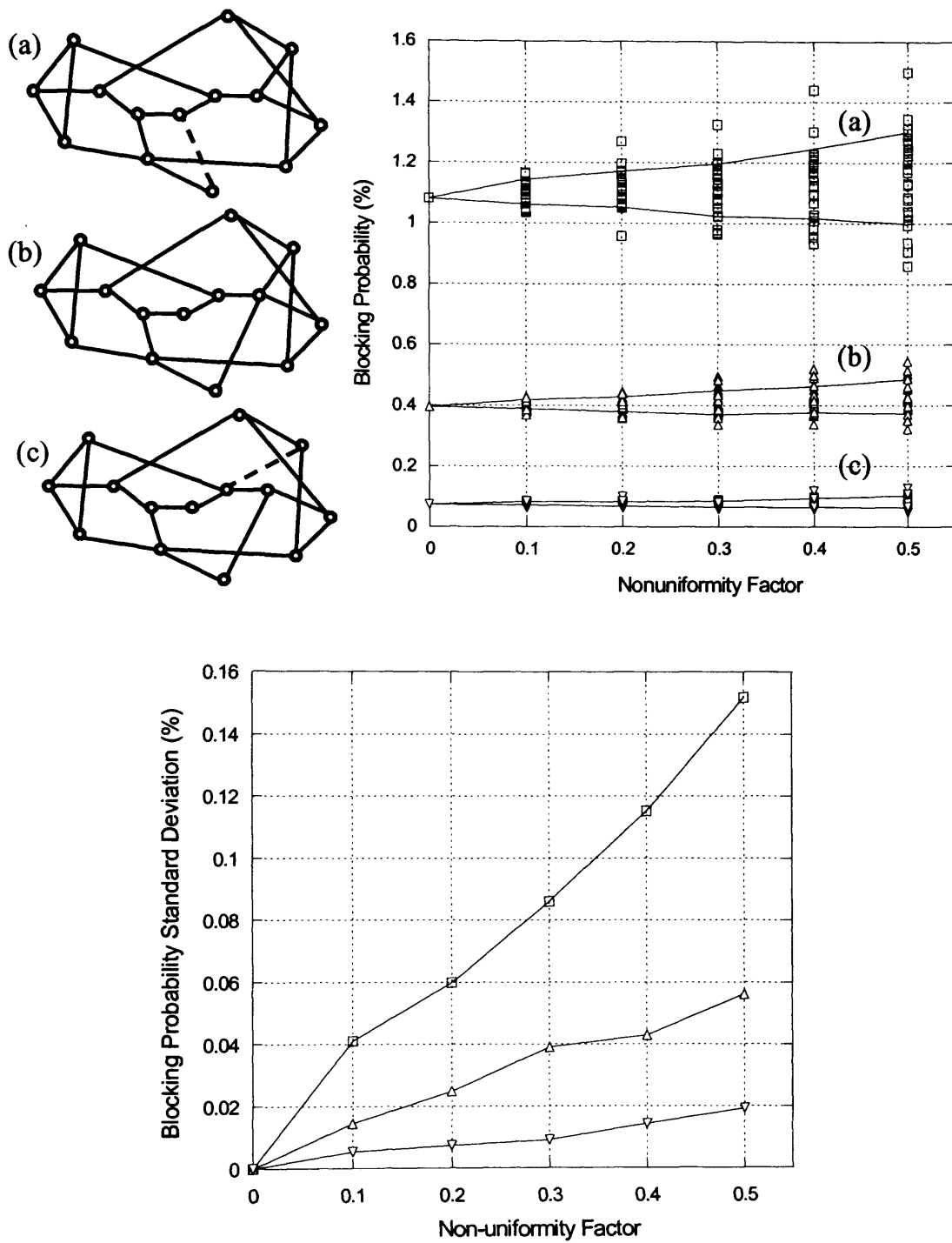


Figure 3.17 – Upper left: (a) worse-performing NSFNET-modified topology (b) NSFNET topology (c) better-performing NSFNET-modified topology (dotted lines indicate rearranged links). Upper right: corresponding values of blocking probability for NSFNET and modified topologies. Solid lines are mean  $\pm$  standard-deviation values. Lower: traffic forecast tolerance of the NSFNET & similar networks

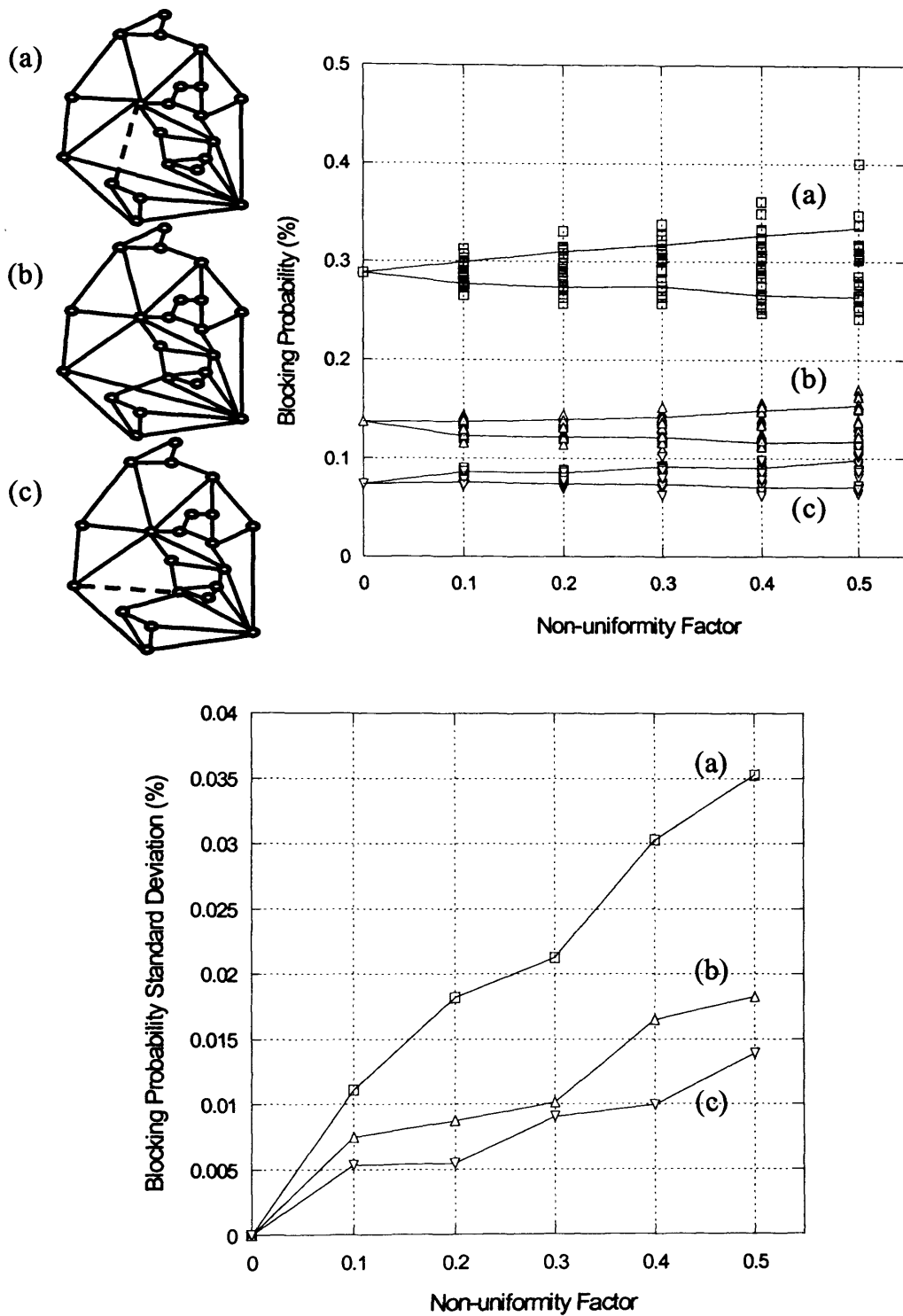


Figure 3.18 – Upper left: (a) worse-performing UKNET-modified topology (b) UKNET topology (c) better-performing UKNET-modified topology (dotted lines indicate rearranged links). Upper right: corresponding values of blocking probability for UKNET and modified topologies. Solid lines are mean  $\pm$  standard deviation values. Lower: traffic forecast tolerance of the UKNET & similar networks



Both NSFNET-modified networks shown in Fig.3.17 have one physical link changed from the original NSFNET network topology. In this study, all three networks were equipped with 16 wavelengths per fibre. Moreover, the same FAR-FF algorithm was employed for wavelength routing. All the networks were tested with a total traffic load of 140 Erlangs. It can be seen that one of the modified networks (c) has a higher forecast tolerance than the original NSFNET network (b). In contrast, the modified network (a) has a much lower traffic forecast tolerance than both the NSFNET network and the modified network (c).

Another practical network, UKNET and its modified networks were tested with the dynamic traffic model. Results are shown in Fig.3.18. All three networks were equipped with 16 wavelengths per fibre and the same FAR-FF algorithm was employed. All three networks were tested with the same total traffic load of 233.3 Erlangs. It can be seen from Fig.3.18 that network (a) has the worst traffic forecast tolerance, i.e. for a given degree of traffic non-uniformity; it exhibits the largest blocking probability standard deviation. Network (c), on the contrary, has the best traffic forecast tolerance, exhibiting the lowest blocking probability standard deviation with increasing load non-uniformity. The UKNET topology has a traffic forecast tolerance between the two modified network topologies.

For both NSFNET and UKNET networks operating under the same conditions, modifying the network topologies by just one physical link leads to large performance variations, and hence different degrees of traffic forecast tolerance. The physical layout of the network topology has been proved to be an important factor in the robustness of the network to future unpredictable traffic pattern changes.

### 3.4 Mathematical model of traffic forecast tolerance

In this section, analytical methods for calculating blocking probabilities with the dynamic traffic model are introduced and discussed. In addition, theoretical results from the analytical model are compared with the simulation results to prove the accuracy of the simulations.

### 3.4.1 Mathematical model comparison

Many studies have been carried out to analyse the performance of wavelength-routed optical networks, such as blocking probability and link utilization rate. The aim of analysing networks using a theoretical methodology is to facilitate the network dimensioning and link capacity to achieve a certain performance. The studies in the literature are classified into two categories: analytical methods for wavelength-routed optical networks with wavelength conversion and analytical methods for wavelength-routed optical networks without wavelength conversion. Some of the analytical methods are inherited from analysing telephony networks, in which case the optical network is equipped with full wavelength conversion, and can be regarded as a conventional circuit-switched telephone network. However, while channels on a telephone network link are indistinguishable, the wavelengths on a wavelength-routed optical network are distinct. One of the major differences of wavelength-routed optical network from conventional circuit-switched networks is that the wavelength continuity constraint introduces load correlation between links, which is not the case with conventional circuit-switched networks, since the wavelength may not be the same along all the physical links from source node to destination node in such networks. In the wavelength-routing model, a traffic request is accepted if there exists at least one wavelength which is idle on all links which make up the route of this request. Hence, many studies analysed the effect of the wavelength continuity constraint on the network performance.

In all these performance analysis studies, some of the standard assumptions used for circuit-switched networks are inherited: the traffic connection requests arrive at each node according to a Poisson process with rate  $\gamma$ , and the destination node for each connection request is uniformly distributed among all the other nodes. The request connection holding times are exponentially distributed with mean  $\frac{1}{\mu}$ , often set to unity. However, several issues make the analysis of blocking probability more difficult for wavelength-routed optical networks compared to conventional circuit-switched networks. First of all, the *Link Independence assumption* is the standard assumption used in the analysis of circuit-switched networks, that the events on different links are independent and, hence, the blocking probability for a path can be

expressed in product form. However, in wavelength-routed optical networks, the correlation between wavelength utilizations on adjacent links is strong. Therefore, the blocking probability computed by assuming link independence might be significantly overestimated or underestimated, especially when the network topology is sparsely connected. This is shown and discussed in Sections 3.4.2 and 3.4.3. Secondly, the *Wavelength independence assumption* that the individual wavelengths are utilised with a fixed probability independent of the utilizations of other wavelengths on the same link again tends to overestimate the blocking probability. Thirdly, *the effect of wavelength selection algorithms* should also be taken into consideration. It is obvious that the distribution of the load over the wavelengths depends on the wavelength selection algorithm. Many studies in the literature assume identical traffic load distributions on all wavelengths on the same link, which is accurate for load-balancing wavelength selection algorithm such as the random wavelength selection. However, it is different for wavelength packing algorithms such as the first-fit and most-used wavelength selections algorithms, which offer much lower blocking probabilities than random wavelength selection. The analytical models for wavelength packing algorithms are more complicated and have a higher computational complexity.

A number of the earliest performance analyses appeared in the literature in the same year. They are [Bar96], [Kov96], and [Bir96]. In [Bar96], the link independence assumption was refined to incorporate the load dependence on successive links. A Markov link correlation model was used to calculate the path blocking probability in the wavelength-routed network with random wavelength assignment. Furthermore, [Bar96] investigates the effects of path length, switch size, and interference length (the expected number of hops shared by two sessions which share at least one hop) on the performance of blocking probability and influence of wavelength conversion. [Kov96] proposed an analytical model to evaluate the benefits of wavelength converters. Both link and wavelength independences are assumed in the model. However, the model is based on Fixed-Routing and Random Wavelength Selection algorithms; hence only one shortest path is considered for each network node-pair. The path blocking probability in a network is computed using the reduced load approximation; meanwhile the Erlang fixed point equations are used to compute the link blocking probability in a recursive algorithm. The independence assumptions

make the model more accurate with densely connected networks, whereas they overestimate the blocking probability for sparsely connected networks such as rings. A generalised reduced load approximation is used in [Bir96] to compute the blocking probability for the Least-Loaded Routing algorithm with a random wavelength assignment algorithm in a fully connected network. Fixed-Routing with random wavelength assignment is also analysed using the same load approximation method. Link independence is assumed in the model. Moreover, the large computational complexity of the generalized reduced load approximation considerably restricts the size of the network that can be analysed. The model is very sensitive to traffic demand changes and gives inaccurate results when the traffic load is low. A less computationally expensive model for the fixed shortest path routing with random wavelength assignment algorithm is presented in [Sub96]. The model does not assume link and wavelength independence, but uses the Markov correlation model instead. More recently, a new analytical technique based on generalized reduced load approximation was proposed in [Sri04], which is applicable to arbitrary topologies and traffic patterns. The major feature of the analytical model is that it takes link load correlation introduced by the wavelength continuity constraint into consideration. Furthermore, the link load correlation method is improved by a modified wavelength independence assumption. Hence, more accurate results can be obtained by the enhanced model. The model is by far, to the best of the author's knowledge, the most accurate analytical model in the literature. It not only has a low computational complexity, but also has high insensitivity to the amount of traffic load, the network topology, and the number of wavelengths. It is claimed that the model can give relatively accurate results for 64 wavelengths even for sparsely connected networks. The model is further extended to take alternate routing into account in the form of FAR and LLR. However, the only drawback is that the model is based on random wavelength assignment, as it is more complicated to describe the packing wavelength algorithms analytically.

Besides random wavelength selection algorithms, an analytical model based on packed wavelength algorithms was first proposed in [Mok98]. The model is designed to calculate the blocking probability with FAR-FF RWA algorithm. The model ignores the real characteristics of overflow traffic and assumes the overflow traffic to have Poisson characteristics to reduce computational complexity. Details of this

model are discussed in Section 3.4.2. An overflow model considering the overflow traffic was proposed in [Kar98] to compute the blocking probability for the FR-FF RWA algorithm. The model uses the reduced load approximation (this technique is sometimes referred to as the Erlang fixed-point equation [Kar98]) to calculate lightpath request arrival rates more accurately. It is assumed that all the incoming Poisson distributed traffic is offered to the first wavelength in the wavelength set. The traffic that cannot be carried over the first wavelength (overflow traffic) is then offered to the second wavelength in the wavelength set, and so on. A technique, the equivalent random method [Har97] [Gir90] [Hui90], is used to compute the blocking probability by taking the peakedness of the non-Poisson overflow traffic into account. However, due to the iterative nature of the algorithm, the analytical model comes with high computational complexity. It is suggested in [Kar98] that the model is more accurate for highly connected topologies and poor for sparsely connected topologies. Moreover, the successive application of the equivalent random approximation brings side effects, in that the accuracy of the model decreases as the number of wavelengths increases. In [Lan01], the first analytical model based on adaptive routing and full wavelength conversion was proposed. The model does not use the link independence assumption. Instead, it accounts for the dependence between the use of wavelengths on successive links of a lightpath and uses a lossless model where blocked traffic requests are retried at a later time. It is claimed that the analytical model not only works well with symmetric networks such as torus and hypercube networks, but also with high and low levels of traffic load. However, the model assumes that each network node is equipped with full wavelength conversion exactly like a telephony circuit-switched network, which is not very practical for the near-future wavelength-routed optical network with wavelength continuity constraint.

Many open problems in this area of study still exist. First of all, to the knowledge of the author, all the analytical methods proposed in the literature are based on Poisson traffic characteristics. As discussed in Section 3.2.2, the backbone Internet traffic exhibits a long-range dependence and heavy-tail nature. There is a lack of theoretical support for analysing the non-Poisson nature of Internet traffic. This is one of the reasons why dynamic traffic models are based on Poisson traffic, since further analysis can be carried out. Secondly, most of the existing routing and wavelength allocation algorithms and related analysis in the literature are centralized. In the

future, distributed algorithms are required for simplicity and scalability purposes. Thirdly, the accuracy of many of the proposed analytical methods are sensitive to the amount of offered network load, network physical topology, and network dimensioning. Many methods are only suitable for small networks and low levels of network load. In particular, many of the analytical methods show increasing inaccuracy with an increase in the number of wavelengths. Last, but not least, as discussed in Section 3.2.3, adaptive routing algorithms, such as AUR-E, have been proven to give the best performance amongst the routing algorithms. However, only a few papers have proposed analytical models based on adaptive routing. This is due to the difficulties of accurately estimating the status information, and combining it with the routing decision using an analytical process.

In general, trade-offs can always be found amongst analytical models. Every analytical model comes with both advantages and disadvantages. As discussed, models with high accuracy normally have high computational complexity. Most analytical models are conditional to a certain degree. Some models are sensitive to the amount of traffic load, some models are better with well connected network topologies but worse with sparsely connected network topologies, some models can only work with a low number of wavelengths. Although some assumptions have to be made to simplify the modelling process, it is those assumptions that restrict the accuracy of models in practice. Regardless of the issues with constructing mathematical models, the analytical process can help to further explain the reasons behind the experimental results and can always be used as a reference.

### **3.4.2 Integration of the traffic model into analytical process**

In this section, the method of combining the dynamic traffic model and the analytical calculation of blocking probability is introduced and discussed in detail. Results from the analytical model are presented and compared with the simulation results from Section 3.4.3. It was explained in Section 3.2.3 that the random wavelength selection algorithm yields results that are much worse than wavelength packing algorithms in terms of blocking probability performance. In addition, all the simulation results were obtained using a wavelength packing algorithm. Hence, it would be incorrect to use an analytical model developed for random wavelength selection, even the most accurate

analytical model in [Sri04] as mentioned in the previous section. AUR-E, the best-performing RWA algorithm has been employed in the simulation, however, to the best of the author's knowledge, to date, there is no analytical technique developed to analyse the performance of AUR-E. Hence, the model developed in [Mok98] was chosen to analyse the simulation performance using the FAR-FF RWA algorithm. On the one hand, it is relatively inexpensive in computational complexity; on the other, it works well with many different types of network topologies. As mentioned in previous section, an improved model [Har97] [Gir90] [Hui90] has been proposed to enhance the accuracy of the calculation of the overflow traffic in the model of [Mok98], however the improved model requires large additional computational complexity and make it impractical to test large scale networks and sparsely connected networks. The analytical process is based on [Mok98] model and is combined with the generation of dynamic traffic pattern as described in section 3.2.2.

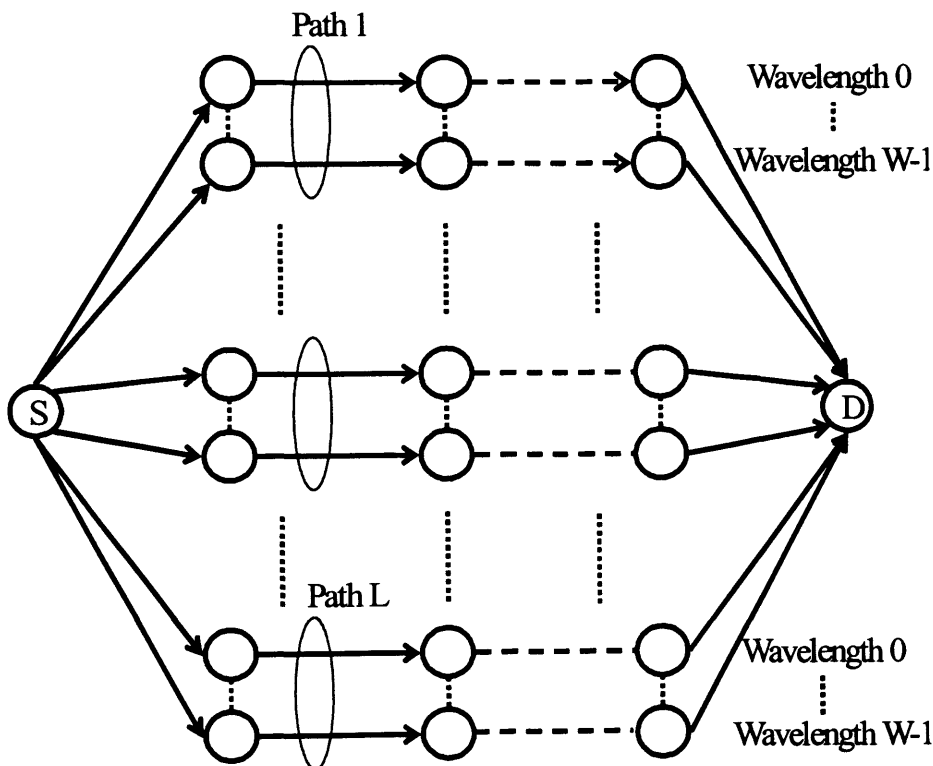


Figure 3.19 – A node-pair path tree without wavelength conversion.

S: the source node; D: the destination node; Path 1 & Path L: alternate physical paths between source node and destination node; Wavelength 0 & Wavelength W-1: wavelength paths for each physical path between the node-pair

The FAR-FF RWA algorithm can be explained using the schematic in Fig.3.19. In fixed alternate routing, every source-destination (s-d) node-pair, as shown in Fig. 3.19, is assigned a set of  $L$  alternate paths. These alternate paths are usually the shortest paths between the source and destination nodes. To respond to a connection request for the node-pair and establish a lightpath between the source and the destination, the path set is searched in a fixed order. It should be noticed that these  $L$  paths are edge-disjoint, a feature to protect the network in case of link failures and to enhance fault tolerance. On each physical path, the wavelength set is also searched in a fixed order to find an available wavelength with which the request can be set up (no wavelength conversion and hence the wavelength continuity constraint is assumed). Therefore, the search for a physical path and a wavelength may be regarded as a search over a sequence of  $LW$  logical paths in the path tree, where a logical path is the combination of a physical path and a distinct wavelength. Consider the search starting from the first logical path in the path tree. If any logical path under consideration is viable, then the lightpath can be established instantly. Otherwise, the traffic request is passed from the current logical path to the next logical path. This is the point at which overflow traffic occurs. Finally, if it overflows from the last logical path in the path tree, the request is blocked, since none of the logical paths is available for a lightpath to be set up for the node-pair. The FAR-FF analytical model notations are given as following:

$\beta_r$ : the average arrival rate for  $r$ th s-d node-pair

$1/\mu_r$ : the mean lightpath holding time for  $r$ th s-d node-pair

$\alpha_r$ : the offered load for  $r$ th s-d node-pair in that  $\alpha_r = \beta_r / \mu_r$

$N$ : the number of nodes in the network

$K$ : the number of physical link in the network

$W$ : the number of wavelength in each fibre

$L$ : the number of alternate physical routes for each node-pair

$R$ : the number of s-d node-pairs in the network in that  $R=N(N-1)$

$S$ : denotes the  $K \times RL$  link-path matrix, defined as

$$S_{ij} = \begin{cases} 1 & \text{If link } i \text{ is on the physical path } j \\ 0 & \text{otherwise } S_{ij} = 0. \end{cases}$$

$r$ : the running index for s-d node-pairs of the network



$l$ : the running index for physical alternate paths of each node-pair

$i$ : the running index for logical paths of each node-pair

$w$ : the running index for the wavelengths of each physical link

$z$ : the running index for the physical links of the network

$A_i^r$ : the offered traffic load to the  $i$ th logical path for the  $r$ th s-d node-pair

$\alpha_{zw}^{rl}$ : the offered traffic load on wavelength  $w$  in link  $z$  due to traffic from the  $r$ th node-pair on the  $l$ th alternate physical path.

$\alpha_{zw}$ : the offered traffic load on wavelength  $w$  in link  $z$  due to all traffic streams, i.e.,

$$\alpha_{zw} = \sum_{r=1}^R \sum_{l=1}^L \alpha_{zw}^{rl} \quad (3.7)$$

$x$ : quantity of offered traffic

$\bar{x}$ : the quantity of carried traffic corresponding to the offered traffic quantity  $x$

$P_i^r$ : the blocking probability on the  $i$ th logical path of the  $r$ th node-pair

$P_B^r$ : the total blocking probability of the  $r$ th node-pair

$F_i^r$ : the probability that a request for the  $r$ th node-pair overflows to the  $i$ th logical path

$B_{zw}$ : the probability of utilization of wavelength  $w$  in link  $z$

To calculate the blocking probabilities, assumptions have to be made. It is assumed that the link blocking events are independent. However, the link loads are not independent, in that the wavelength continuity constraint is taken into account. It is also assumed that the wavelengths are statistically independent, but not identically distributed due to the fixed-order wavelength search.

To analyse the occurrence of blocking, the following procedures are carried out:

- 1) Set  $A_0^r = \alpha^r$  and  $F_0^r = 1$ , as the offered traffic load for the  $r$ th node-pair is always offered to the 0<sup>th</sup> logical path first, hence the probability that the traffic request for the  $r$ th node-pair overflows to the 0<sup>th</sup> logical path is 100%.
- 2) For all s-d node-pairs, scan the route trees for each logical path ( $i=0, 1, \dots, LW-1$ ) and approximate the carried load for the  $r$ th node-pair on the  $i$ th logical path:

$$\bar{A}_i^r = A_i^r (1 - P_i^r) = A_i^r \prod_{k=0}^{K-1} (1 - B_{k,i \bmod W})^{S_{k,(r-1)L+[i/W]}} \quad (3.8)$$

for all node-pairs  $r = 1, 2, \dots, R$ .  $i \bmod w$  stands for the wavelength that the  $i$ th logical path is on;  $B_{zw}$  is the probability of utilization of wavelength  $w$  in link  $z$ ,  $1 - B_{k, i \bmod w}$  is the probability of the traffic passing through  $k$  physical links on the  $i$ th logical path. Since link independence assumption is made, the probability of the traffic passing through the whole  $i$ th logical path along every physical link can be described as  $\prod_{k=0}^{K-1} (1 - B_{k, i \bmod w})$ . The parameter

$S_{k, (r-1)L + [i/w]}$  is used to search the  $K \times RL$  matrix to judge whether the  $k$ th physical link is in the  $i$ th logical path under consideration.  $[ ]$  means the integer part of the content inside the brackets.

- 3) Consider the fact that the traffic carried by a link on a logical path for node-pair  $r$  is the same as the traffic carried by the  $r$ th node-pair on that logical path:

$$\begin{aligned} \alpha_{z, i \bmod w}^{-rl} &= \alpha_{z, i \bmod w}^{rl} (1 - B_{z, i \bmod w}) \\ \alpha_{z, i \bmod w}^{-rl} &= A_i^r \prod_{k=0}^{K-1} (1 - B_{k, i \bmod w})^{S_{k, (r-1)L + [i/w]}} \end{aligned} \quad (3.9)$$

for all links  $z$  on the  $l$ th alternate path of the node-pair  $r$ .

- 4) Compute the probability of overflow and the offered traffic to the  $(i+1)$ th

$$\begin{aligned} \text{logical path for node-pair } r \text{ as: } F_{i+1}^r &= F_i^r P_i^r \\ A_{i+1}^r &= A_i^r P_i^r \end{aligned} \quad (3.10)$$

This procedure is repeated until all logical paths of all s-d node-pairs have been processed. In the end of the procedure, the total offered load  $\alpha_{zw}$  for each  $z$  and  $w$  is given as a function of the link-blocking probabilities  $B_{zw}$ . The link-blocking probability is then approximated (overflow traffic is not Poisson) by the Erlang loss formula as:

$$B_{z,w} = E(\alpha_{zw}, 1) = \frac{\sum_{r=1}^R \sum_{l=1}^L \alpha_{zw}^{rl}}{1 + \sum_{r=1}^R \sum_{l=1}^L \alpha_{zw}^{rl}} \quad (3.11)$$

$B_{zw}$  has to be solved for all  $z$  and all  $w$ . Once the values of  $B_{zw}$  are obtained, the lightpath-blocking probability of the  $r$ th node-pair is found as:

$$P_B^r = F_{LW}^r \quad (3.12)$$

Since the blocking probability of the  $r$ th node-pair equals the probability of the traffic request overflowing from the last logical path for this  $r$ th node-pair. The average lightpath-blocking probability of the whole network is given as the ratio between the total blocked traffic in the network and the total offered traffic to the network:

$$P_{\text{average\_blocking}} = \frac{\sum_{r=1}^R P_B^r \alpha^r}{\sum_{r=1}^R \alpha^r} \quad (3.13)$$

Since equations (3.9) and (3.11) are a set of nonlinear equations, an algorithm is required to use the above analytical process with the generation of random traffic patterns. A recursive process is employed to solve the nonlinear equations. If a convergence can be reached, it means that a result can be obtained.

The algorithm is summarised below:

Step 1) set the number of random traffic patterns or simulation runs for each non-uniformity factor

Step 2) generate the random traffic pattern using (3.1), (3.2), and (3.3)

Step 3) set  $B_{zw}(n)$  first,  $n=0$ , as

$$B_{zw}(n) = (B_{0,0}, \dots, B_{K-1,0}, \dots, B_{0,W-1}, \dots, B_{K-1,W-1}) = (0, \dots, 0, \dots, 0, \dots, 0)$$

Step 4) assign the random generated load for each node-pair and overflow probability of the first logical path for each node-pair as

$$A_0^r = \alpha^r, \quad A_0^r = (A_0^0 = \alpha^0, A_0^1 = \alpha^1, \dots, A_0^{R-1} = \alpha^{R-1}) \quad \text{and}$$

$$F_0^r = 1, \quad F_0^r = (F_0^0 = 1, F_0^1 = 1, \dots, F_0^{R-1} = 1)$$

Step 5) calculate  $P_i^r$  using (3.8)

Step 6) calculate  $A_{i+1}^r$  and  $F_{i+1}^r$  using (3.10)

Step 7) calculate every  $\alpha_{z,i \bmod W}^{rl}$  using (3.9) that

$$\alpha_{z,i \bmod W}^{rl} = \frac{A_i^r \prod_{k=0}^{K-1} (1 - B_{k,i \bmod W})^{S_{k,(r-1)L + \{i/W\}}}}{1 - B_{z,i \bmod W}}$$

Step 8) calculate  $\alpha_{zw}$  using (3.7)

Step 9) calculate  $B_{zw}(n+1)$  using (3.11) that  $B_{zw}(n+1) = \frac{\alpha_{zw}}{1 + \alpha_{zw}}$

Step 10) compare  $B_{zw}(n+1)$  and  $B_{zw}(n)$ . If the difference between the two is sufficiently low that  $|B_{zw}(n+1) - B_{zw}(n)| < \varepsilon$ , terminate and go to step 11), otherwise set  $B_{zw}(n) = B_{zw}(n+1)$ . Go back to step 5) and start over again. After a number of iterations of the calculation of  $B_{zw}(n)$ , if the result is not obtained, go to step 2) for another random traffic pattern and start over again.

Step 11) Once all values of  $B_{zw}$  are obtained, calculate  $P'_B$  using (3.12).

Step 12) calculate the blocking probability for the whole network using (3.13).

This iterative process is terminated when all blocking probabilities have been collected for each of the randomly generated traffic patterns.

### 3.4.3 Theoretical results of traffic forecast tolerance with FR-FF

In this section, the results are shown from the analytical model for the FF-FR algorithm. These analysis results are also compared with the simulation results for traffic forecast tolerance. The blocking probabilities are first computed by the analytical model allowing the further calculation of the standard deviation of the blocking probability distribution. The simulation results are computed in parallel to compare with the analytical results. For both analysis and simulation, each standard deviation value is the result for 25 blocking probabilities resulting from 25 randomly generated traffic patterns. All the tested network topologies can be found in Tab.3.2.

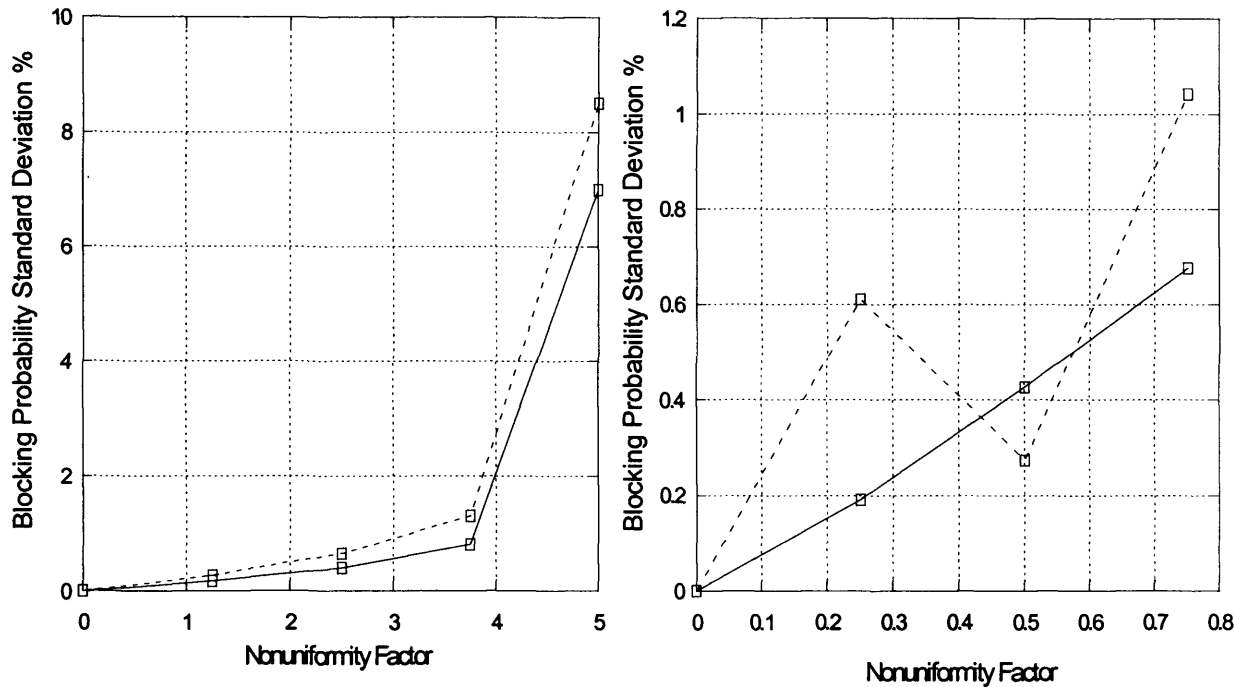


Figure 3.20 – Blocking probability standard deviation versus non-uniformity factor for 6-node-ring with 4 wavelength per fibre (left) and 8 wavelengths per fibre (right).

Solid lines: simulation results; dotted lines: analytical results.

The ring network is chosen because it is the extreme case of sparsely connected network topology. It can be seen from Fig.3.20 that the analytical results are close with the simulation results for small number of wavelength. Even when the non-uniformity factor reaches 100% of mean traffic request inter-arrival period, where extreme traffic scenarios take place, the analysis result exhibits a close match with the simulation result. It can also be seen from Fig.3.20 that the increase of the number of wavelengths makes the analysis results inaccurate and irregular. The non-uniformity factor is chosen at 16.7%, 33.4%, and 50.1% of the mean traffic request inter-arrival period. The analysis results show kinks for the chosen non-uniformity factors. This can be understood that with the increase of wavelength number, the number of logical paths for each node-pair increases as well. This shows the disadvantage of assuming the overflow traffic has Poisson characteristics. Hence, it is suggested that the analytical model does not work well on sparsely connected network topologies with high number of wavelengths.

Further analysis has been carried out on EUROCORE network, a practical network, which is densely connected. The EUROCORE network has 11 network nodes with 25 physical links. It can be seen from Fig.3.21 that the analysis results exhibit close matches with the simulation results for both network dimensioning of 4 and 8 wavelengths per fibre.

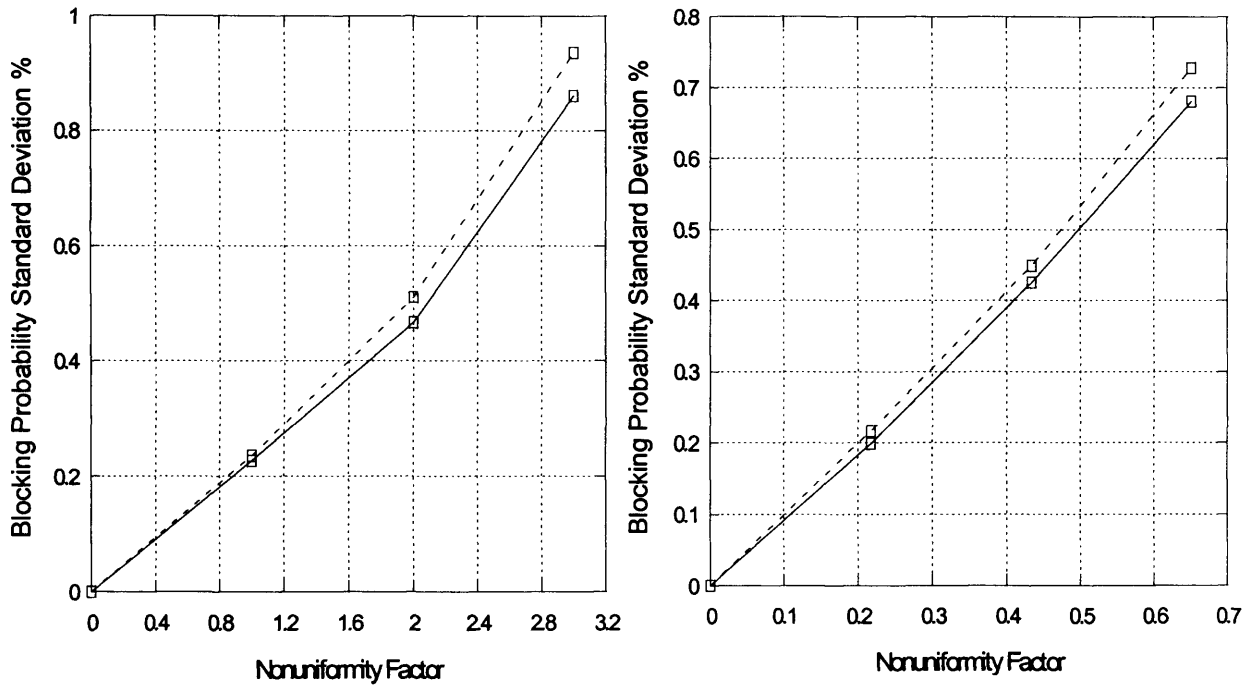


Figure 3.21 - Blocking probability standard deviation versus non-uniformity factor for EUROCORE network with 4 Wavelength per fibre (left) and 8 wavelengths per fibre (right). Solid lines: simulation results; dotted lines: analysis results.

Another practical network, NSFNET, has been tested as well. The results are shown in Fig.3.22. The NSFNET network is less connected than EUROCORE network. It has 14 network nodes with 21 physical links. The non-uniformity factor is chosen at 25%, 50%, 75%, and 100% of the mean request inter-arrival period for both cases of 4 and 8 wavelengths per fibre. The left part of the graph shows the non-uniformity factor ranged between 0 and 75% of the inter-arrival time, whereas the right part of the graph shows the non-uniformity factor ranged between 0 and 100% of the inter-arrival time. It can be seen that under the extreme traffic scenarios the analysis result for FR-FF matches the simulation result for both cases.

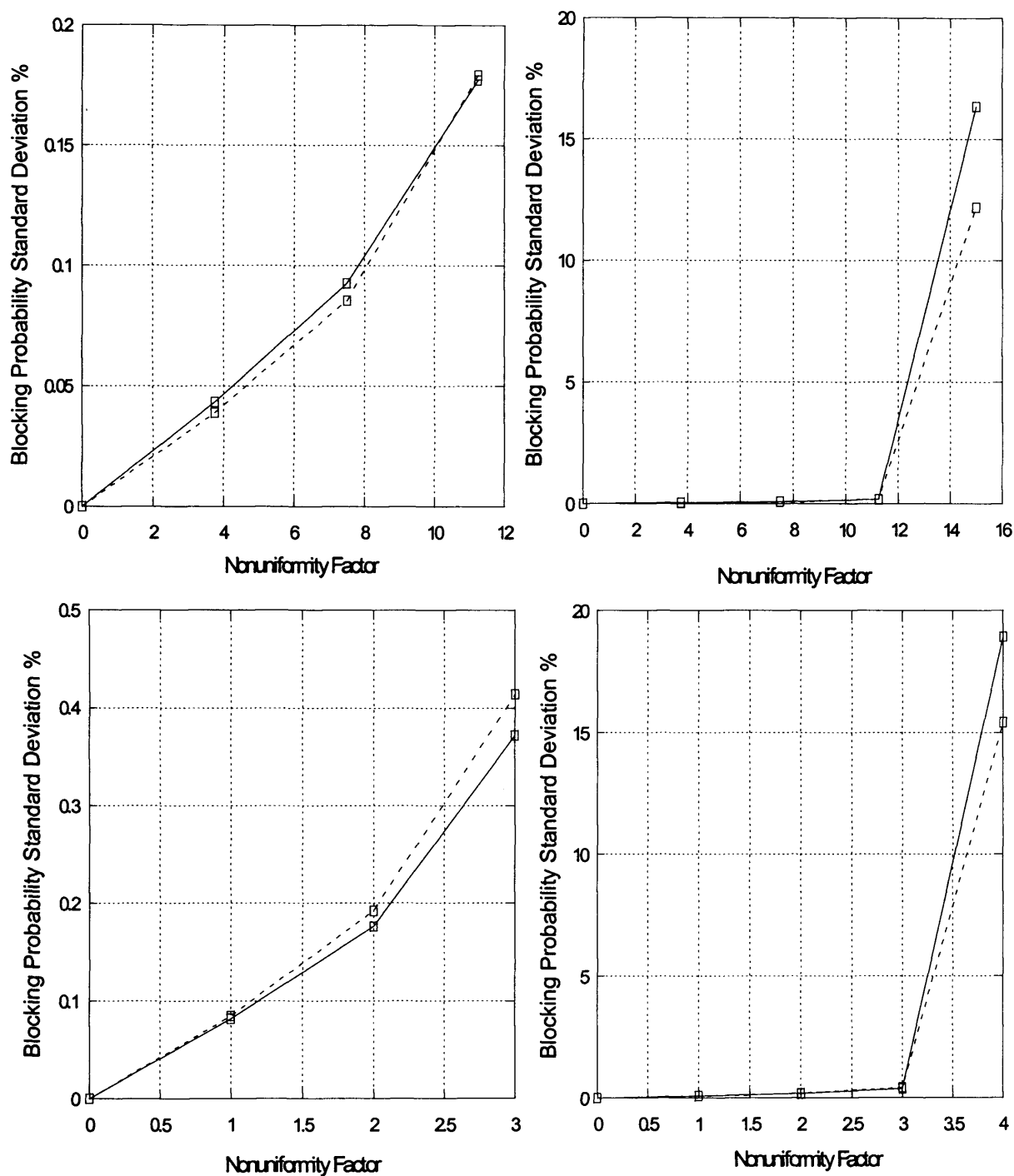


Figure 3.22 - Blocking probability standard deviation versus non-uniformity factor for NSFNET network with 4 wavelength per fibre (upper part) and 8 wavelengths per fibre (lower part). Solid lines: simulation results; dotted lines: analysis results.

A further test has been carried out on a randomly connected network with 15 nodes and 31 physical links, the network topology can be found in Fig.3.5. Compared with NSFNET network, similar results can be found in Fig.3.23.

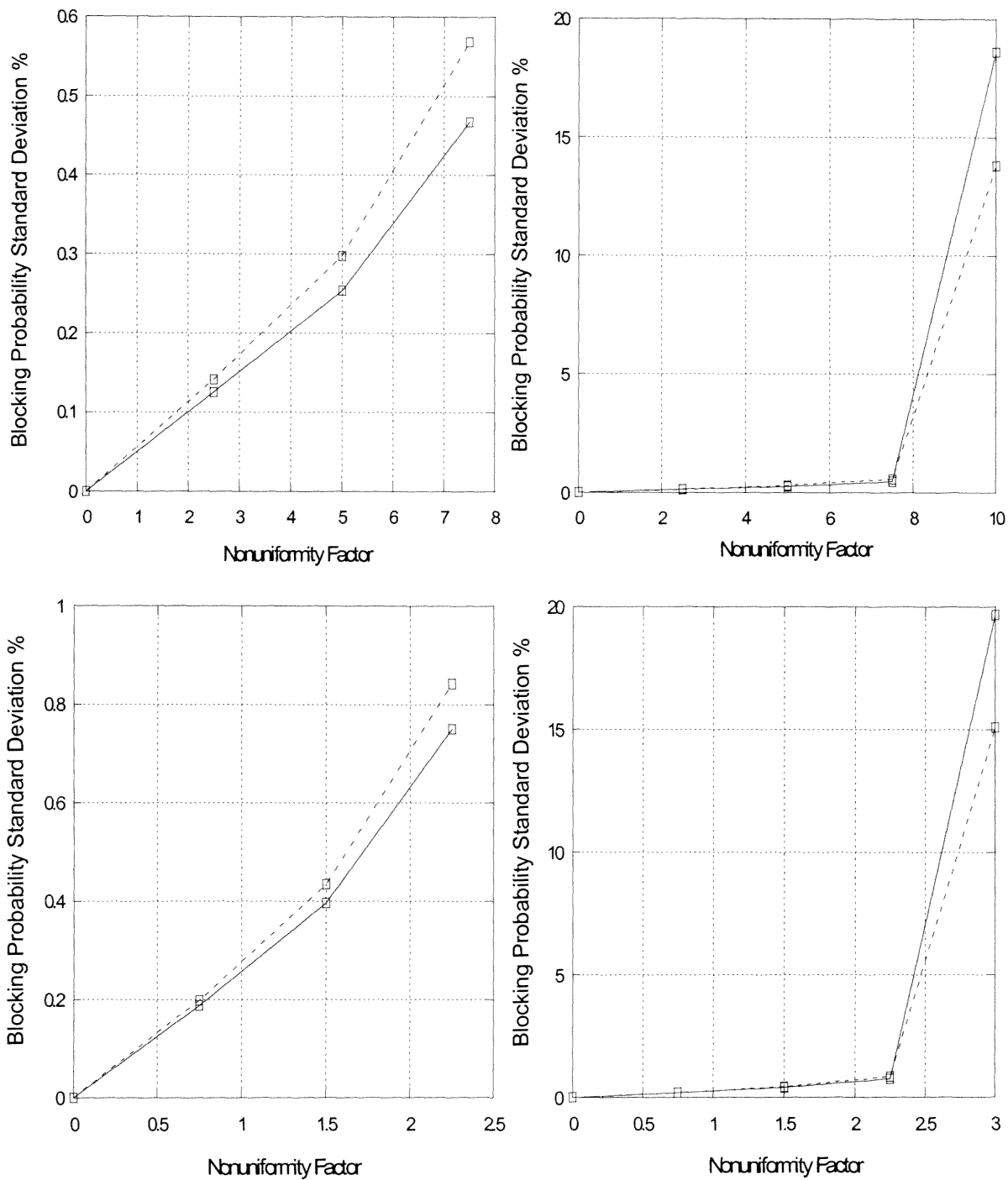


Figure 3.23 - Blocking probability standard deviation versus non-uniformity factor for a randomly connected network with 4 wavelength per fibre (upper part) and 8 wavelengths per fibre (lower part). Solid lines: simulation results; dotted lines: analysis results.

Moreover, the randomly connected network with 16 wavelengths per fibre is tested and compared with NSFNET network with 16 wavelengths per fibre. It can be seen in



Fig.3.24 that analysis has a close agreement with the simulation result for both networks. Both networks were tested with 32 and 64 wavelengths per fibre. However, the analytical model does not generate any meaningful result that can be compared with simulation result. This is caused due to the exponential increase of the number of logical paths in each node-pair.

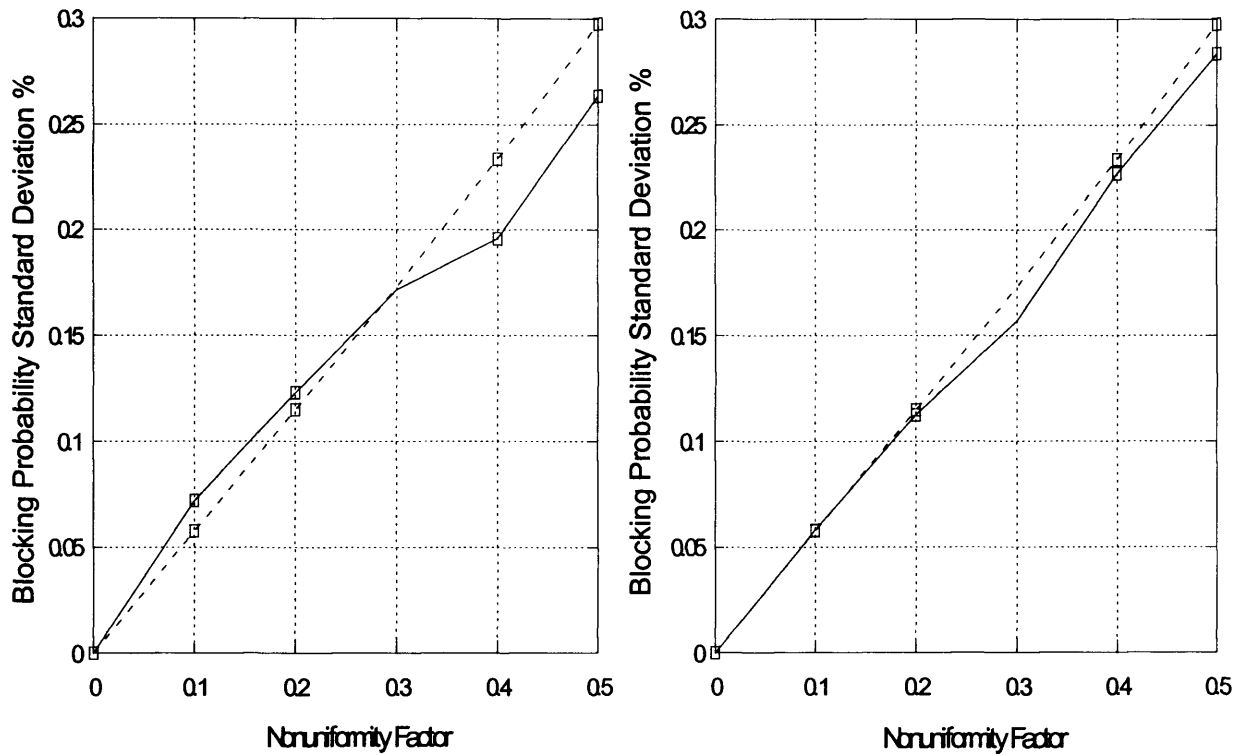


Figure 3.24 - Blocking probability standard deviation versus non-uniformity factor for NSFNET (left) and the randomly connected network (right) with 16 wavelengths per fibre. Solid lines: simulation results; dotted lines: analysis results.

In this section, the analysis and simulation of the traffic forecast tolerance have been compared for different network topologies. The integration of the dynamic traffic model with analytical process is given to assess the robustness of the network to unpredictable traffic pattern changes. The result shows that the simulation gives accurate results, whereas the analytical model gives accurate results under certain conditions. Result also shows that the analytical model is sensitive to the physical topology layout, the number of wavelengths, and the traffic demand. The sensitivity of the analytical model corresponds to the discussion in Section 3.4.1.

### 3.4.3 Theoretical results of traffic forecast tolerance with FAR-FF

In this section, the results are shown from the analytical model for the FAR-FF algorithm. The results for EUROCORE network, NSFNET network, and a randomly connected network are shown respectively with FAR-FF RWA algorithm. For each network node-pair, two distinct physical paths are considered for the routing decision.

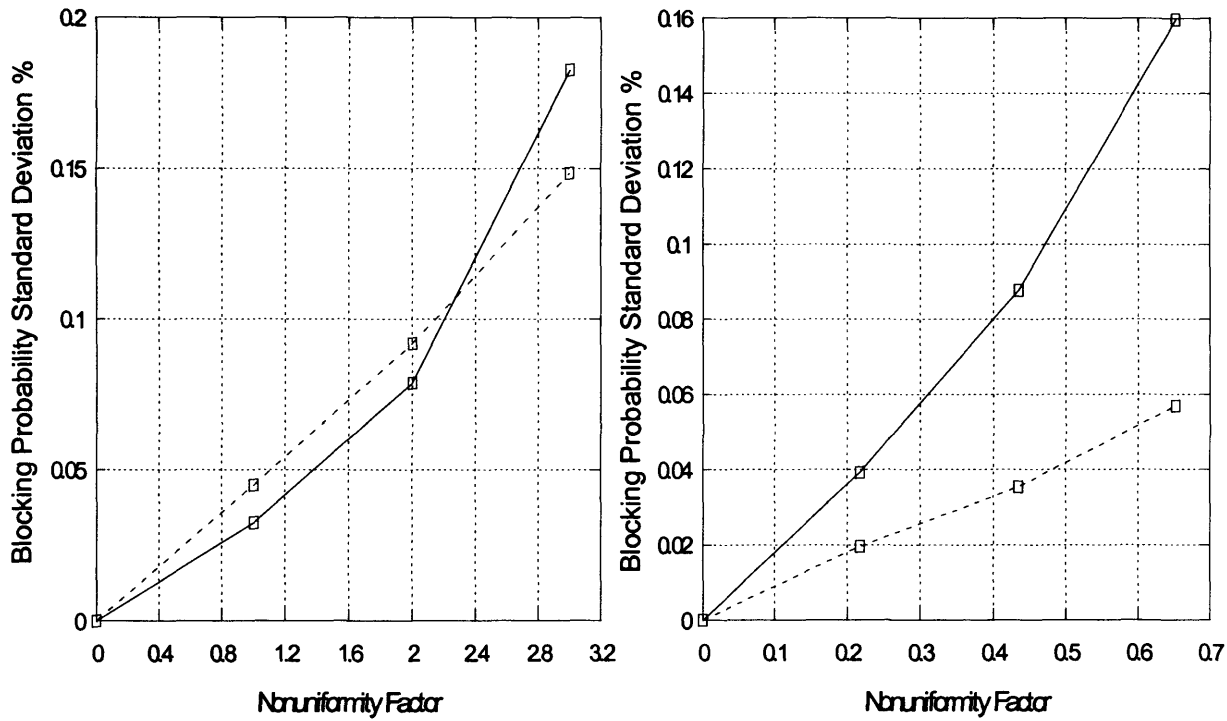


Figure 3.25 - Blocking probability standard deviation versus non-uniformity factor for EUROCORE network with 4 Wavelength per fibre (left) and 8 wavelengths per fibre (right). Solid lines: simulation results; dotted lines: analysis results.

Compared with Fig.3.21, it should be noted that the analysis result of FR-FF shows a closer agreement with the simulation result than that of FAR-FF. This is due to the increase of the number of logical paths for each node-pair, as FAR-FF takes two physical paths into consideration. In the analysis, traffic overflows happen more often than in the FR-FF case, which makes the effects of assuming that the overflow traffic has Poisson statistics more obvious. In Fig.3.25, it should also be noted that the analysis result of 4 wavelengths per fibre is closer with the simulation result than that of in the case of 8 wavelengths per fibre. Again, the increased number of logical paths makes the analytical results inaccurate.

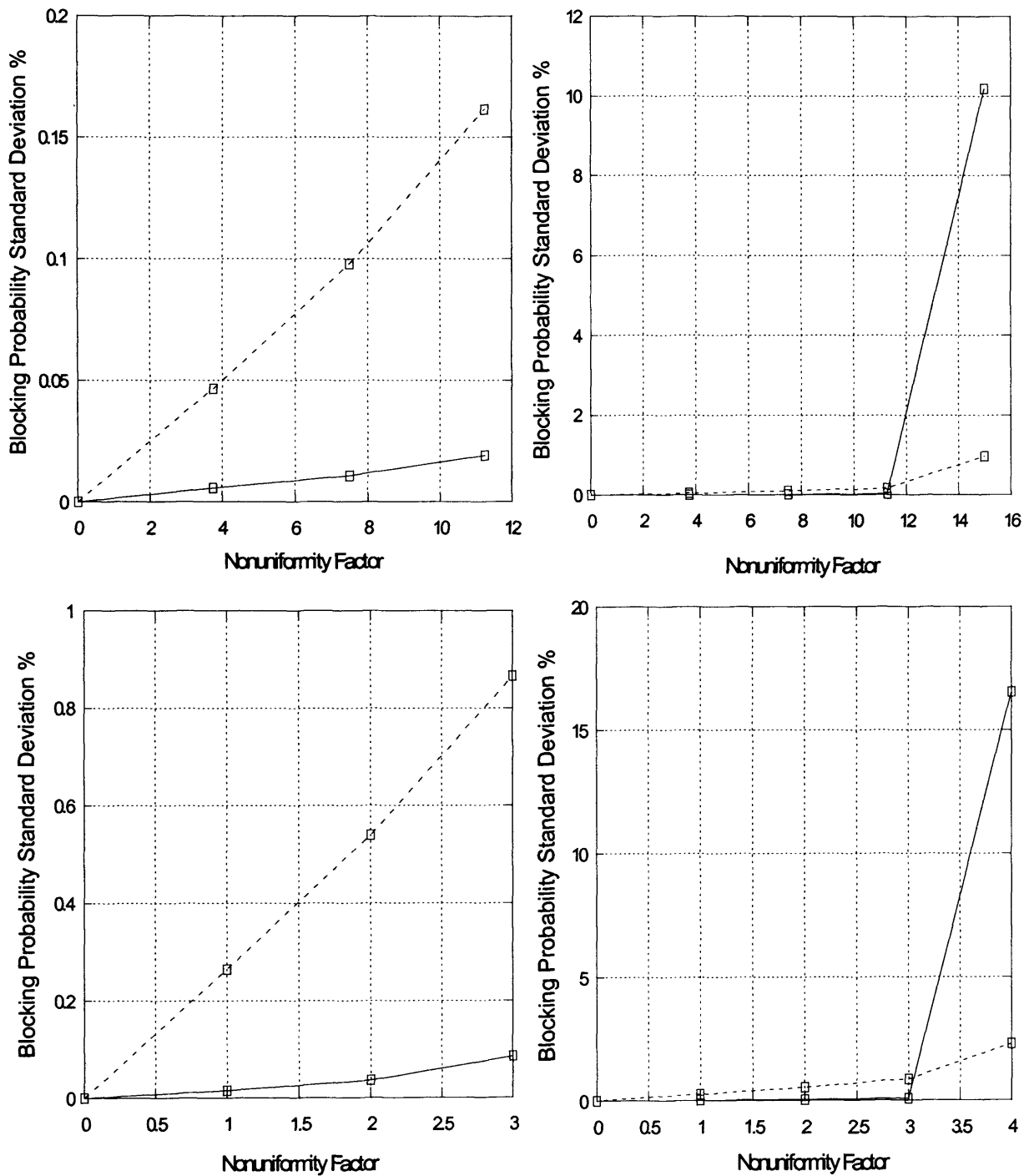


Figure 3.26 - Blocking probability standard deviation versus non-uniformity factor for NSFNET network with 4 wavelength per fibre (upper part) and 8 wavelengths per fibre (lower part). Solid lines: simulation results; dotted lines: analysis results.

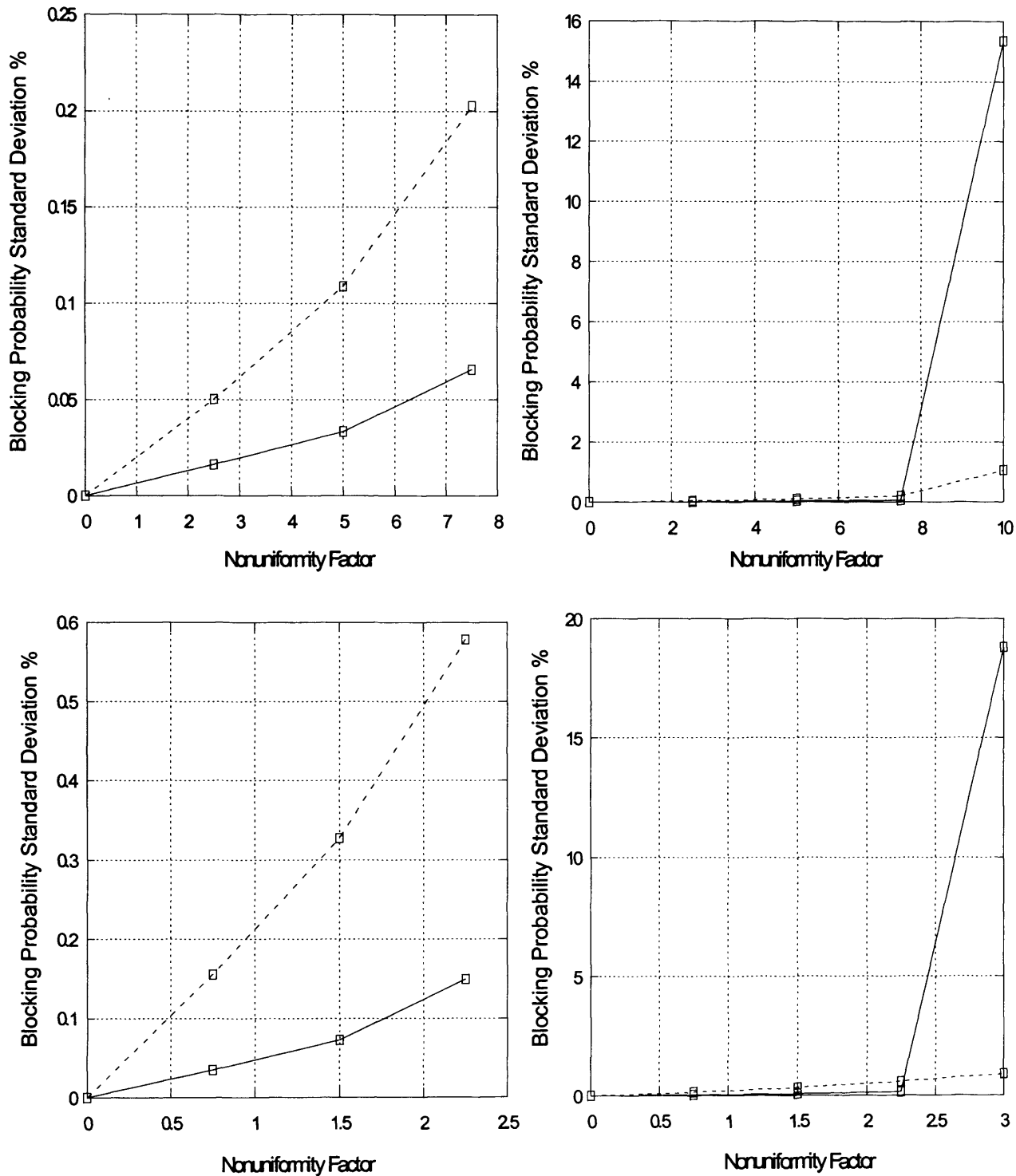


Figure 3.27 - Blocking probability standard deviation versus non-uniformity factor for a randomly connected network with 4 wavelength per fibre (upper part) and 8 wavelengths per fibre (lower part). Solid lines: simulation results; dotted lines: analysis results.

In Fig.3.26 and Fig.3.27, for both NSFNET network and the randomly connected network, the right parts show the extreme traffic scenarios where the non-uniformity factor is equal to the traffic request inter-arrival period. It can be observed that the analytical results have largely increased compared with the non-extreme traffic situations. However, the results from the theoretical analysis show a large discrepancy with the simulation result. Whereas, under the non-extreme traffic environment (left parts of Fig.3.26 and Fig.3.27), the analytical model overestimates the blocking probability due to the assumption of the overflow traffic having Poisson characteristics. For both networks, the discrepancies in the case of 8 wavelengths per fibre are more obvious than in the case of 4 wavelengths per fibre. This is again due to the increased number of logical paths that increases the overestimation using the analytical model.

### 3.5 Summary

In this chapter, a review of traffic distribution models was presented, followed by a detailed introduction to a novel dynamic traffic model. The traffic model can generate a variety of traffic distributions with the same total traffic volume, but with different degree of non-uniformity and asymmetry. In addition, the traffic model can describe extreme traffic pattern scenarios, and can be easily controlled by one parameter defined as the non-uniformity factor. Secondly, a review of routing and wavelength allocation (RWA) algorithms was presented, considering the tradeoffs between the computational complexity and the blocking probability performance. A ranking of the different RWA algorithms was given according to their performance. Thirdly, the proposed dynamic traffic model was tested with different RWA algorithms (FR-FF, FAR-FF and AUR-E) for a range of network topologies. The tested network topologies ranged from the least sparsely connected network, i.e. ring networks, to densely connected network, i.e. mesh/practical network topologies and randomly connected network. The network performance with extreme traffic statistics were further investigated using the dynamic traffic model and the range of blocking probabilities was shown to significantly increase with extreme traffic load non-uniformity. Next, a method to quantify traffic forecast tolerance (TFT) was defined. The traffic forecast tolerance was then investigated by analytical methods integrated

with the dynamic traffic model. The analytically obtained values of TFT were presented in comparison with the simulation results for different type of network topologies, showing excellent agreement for the case of FR-FF RWA algorithm with a lower number of wavelength per fibre, but reduced accuracy for FAR-FF due to the approximation of the statistics of the overflow traffic with Poisson distributions.

In summary, the results suggest that traffic forecast tolerance is strongly dependent on the RWA algorithm and the network physical topology (small changes in the physical link layout were shown to lead to large variations in the network tolerance). Furthermore, the results suggest that networks with low blocking probability under uniform traffic loading tend to show higher traffic forecast tolerance.

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## **Chapter 4 Investigation of the Impact of Network Topology on Traffic Forecast Tolerance**

### **4.1 Introduction**

It was shown in chapter 3 that small topological changes to a network may lead to large variations of its tolerance to unpredictable traffic patterns. In particular, just changing the location of a single physical link in the network can lead to large performance differences, despite all other network parameters being kept the same.

Therefore, it is of great importance to carry out the design of wavelength-routed optical network topology to ensure sufficient robustness to accommodate rapid dynamic traffic pattern changes. In addition, network expansion and upgrading are always ongoing processes in practice. In this case, it is essential to ensure the optimum positioning of new network nodes and links, together with the allocation of additional resources, based on the original network topology to maximise the network's traffic forecast tolerance.

In this chapter, a study of the relationship between network physical topology and network traffic forecast tolerance is described. A large number of network topologies are tested to assess the traffic forecast tolerance. In particular, the average lightpath length in the wavelength-routed network and the wavelength requirement in static network design are investigated.

### **4.2 Lightpath Length and Traffic Forecast Tolerance**

#### **4.2.1 Average Path Length in Theory**

The average path length is one of the important parameters that is governed by the network topology. Many studies have been carried out regarding this in the field of graph theory. The average path length in the graph is defined as the sum of the lengths (often referred to as the number of hops) of the shortest paths for all the node-pairs in

the network, divided by the number of node-pairs. In this section, a simple equation is derived to calculate the average number of hops between any two nodes in a network with  $n$  nodes and average nodal degree of  $\delta$ . The equation is derived from the Moore bound in [Big93], which gives the maximum number of nodes in a graph of diameter  $D$  (the longest shortest path among all the node-pairs) and maximum nodal degree  $\delta_{\max} > 2$ .

$$n \leq 1 + \delta_{\max} \sum_{h=1}^D (\delta_{\max} - 1)^{h-1} = 1 + \delta_{\max} \frac{(\delta_{\max} - 1)^D - 1}{\delta_{\max} - 2} \quad (4.1)$$

From equation 4.1, it is straightforward to obtain the minimum value for the network diameter,

$$D_{\min} \geq \frac{\ln \left[ 1 + (n-1) \frac{\delta_{\max} - 2}{\delta_{\max}} \right]}{\ln(\delta_{\max} - 1)} \quad (4.2)$$

Since the network diameter is the longest shortest path in the shortest path set for all the node-pairs, if the maximum nodal degree  $\delta_{\max}$  is replaced with average nodal degree  $\delta$  in equation 4.2, the average shortest path (the average number of hops) between any node-pairs can be approximated as:

$$h \approx \frac{\ln \left[ 1 + (n-1) \frac{\delta - 2}{\delta} \right]}{\ln(\delta - 1)} \quad (4.3)$$

When  $n$  is close to the value of  $\delta + 1$ , equation 4.3 becomes:

$$\frac{\ln \left[ 1 + (n-1) \frac{\delta - 2}{\delta} \right]}{\ln(\delta - 1)} \xrightarrow{n \rightarrow \delta+1} 1 \quad (4.4)$$

This means that, for the fully connected network, every node has a link to every other node in the network, hence the the average path length is therefore 1. In addition, when the number of nodes becomes infinity, equation 4.3 becomes:

$$\frac{\ln \left[ 1 + (n-1) \frac{\delta - 2}{\delta} \right]}{\ln(\delta - 1)} \xrightarrow{n \rightarrow \infty} \frac{\ln \left[ \frac{n(\delta - 2)}{\delta} \right]}{\ln(\delta - 1)} \quad (4.5)$$

The theoretical analysis gives the approximate range of the average path length

between 1 and  $\frac{\ln\left[\frac{n(\delta-2)}{\delta}\right]}{\ln(\delta-1)}$ . This approximation process was shown to be valid for

networks with average nodal degrees higher than 3 through experiments. The approximation becomes inaccurate when the average nodal degree is between 2 and 3. It should be noted that there is a difference between the average lightpath length and the average path length in the network assuming shortest path routing, though they are highly related to each other. The lightpath is usually established on the shortest physical path for each node-pair, meaning that the established lightpath length is equal to the length of the shortest path, since most of the routing decisions are based on the shortest path routing. However, this is true only when the RWA algorithm considers the shortest path for each node-pair, i.e. FR-FF algorithm, whereas in the case of alternate routing, i.e. FAR-FF, the situation is quite different, since the second shortest path, the third shortest path, etc are considered. Moreover, if the RWA algorithm is adaptive and based on wavelength graph, i.e. AUR, the average lightpath length may be far from the theoretical value of average path length, since the RWA algorithm literally considers every possible physical route between the source and destination nodes as long as it can find an available wavelength along the route. Hence, equation 4.3 can be used as the lower bound for the average lightpath length.

#### 4.2.2 Average Lightpath Length with Practical and Randomly Connected Networks

It was shown in Chapter 3 that a small change in a network's physical topology may lead to a large variation in its traffic forecast tolerance. The established lightpath length is hence calculated through simulations for a range of practical networks with a variety of RWA algorithms.

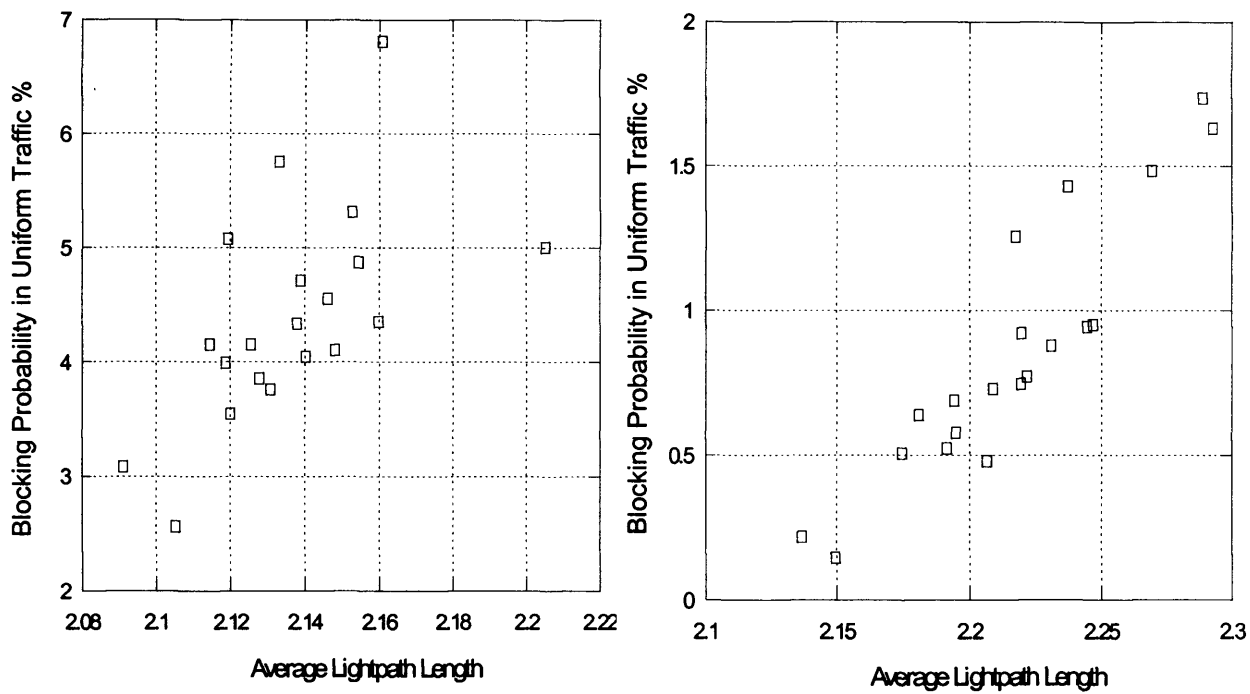


Figure 4.1 - Average lightpath length versus blocking probability in uniform traffic for NSFNET & NSFNET-similar networks. Left: FR-FF algorithm; right: FAR-FF with 3 alternate paths for each node-pair.

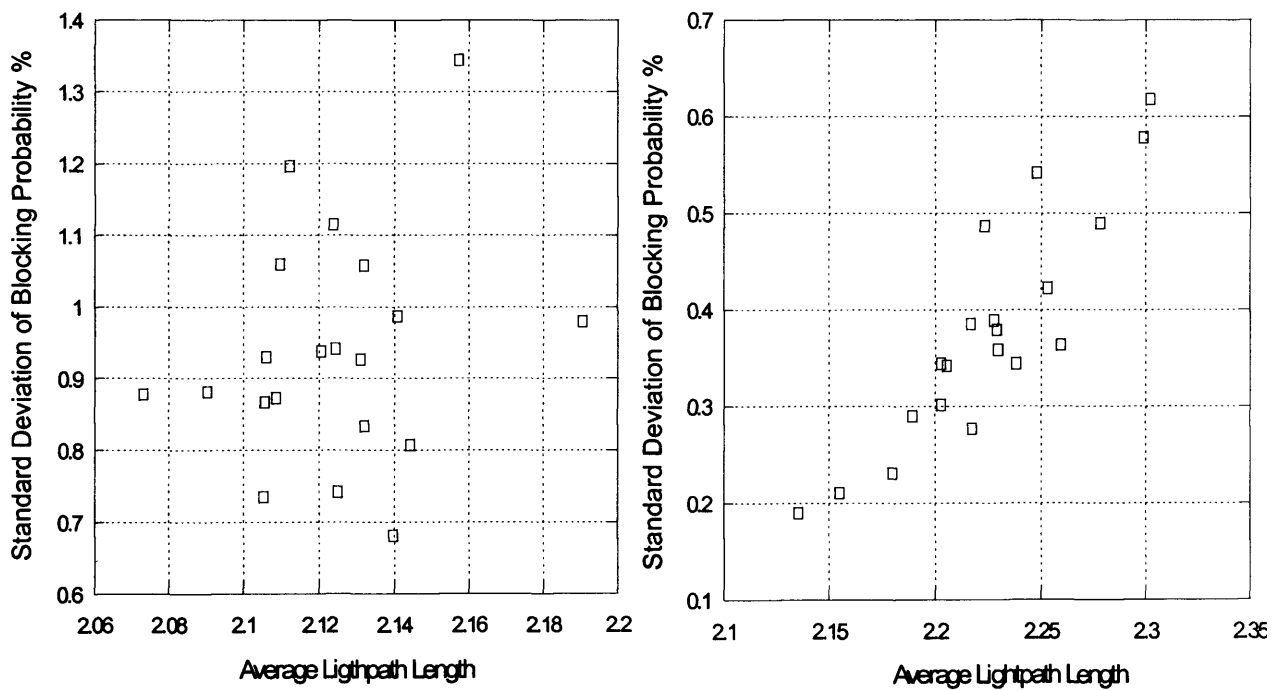


Figure 4.2 - Average lightpath length versus standard deviation of blocking probability distribution for NSFNET & NSFNET-similar networks (the non-uniformity is of 80% of the mean request inter-arrival period). Left: FR-FF algorithm; right: FAR-FF with 3 alternate paths for each node-pair.

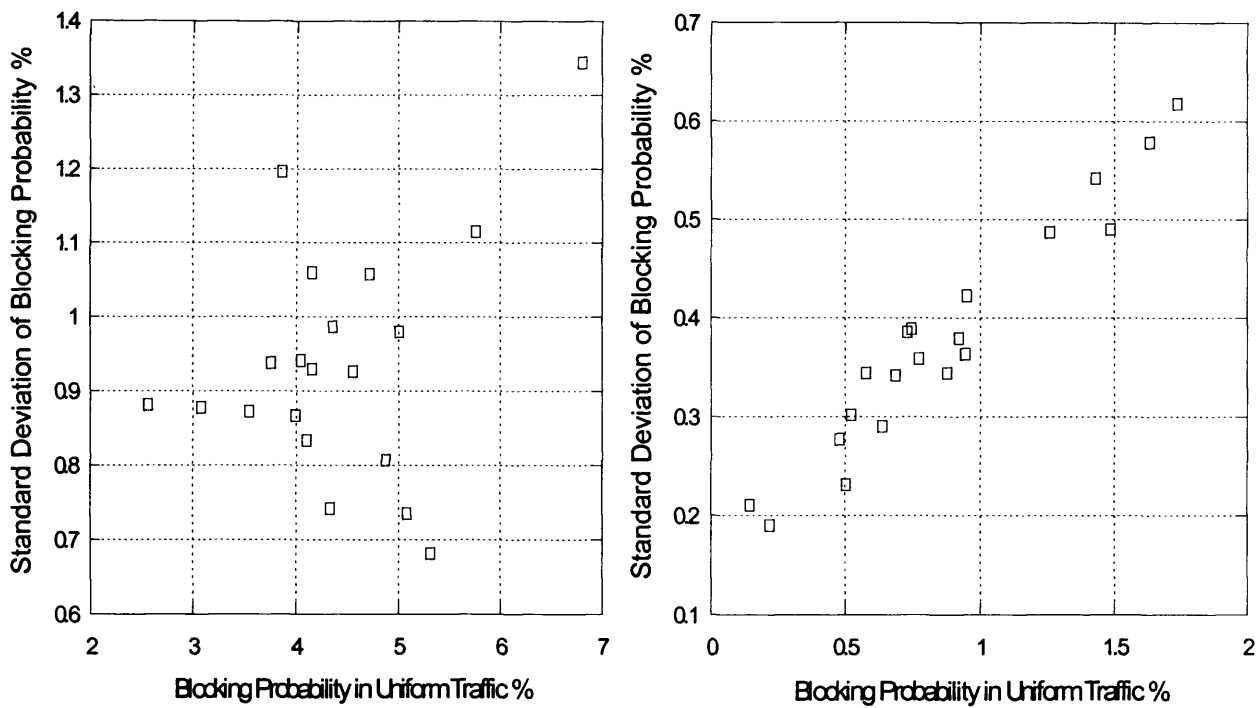


Figure 4.3 - Blocking probability in uniform traffic versus standard deviation of blocking probability distribution for NSFNET & NSFNET-similar networks (the non-uniformity is of 80% of the mean request inter-arrival period). Left: FR-FF algorithm; right: FAR-FF with 3 alternate paths for each node-pair.

Two practical network topologies, NSFNET and UKNET, and a randomly connected network, RANNET (Fig.3.5), together with a series of similar network topologies obtained by modifying the position of one physical link, were tested with a variety of RWA algorithms to investigate the correlation between the average lightpath length and the traffic forecast tolerance. The physical link modifications from the original network topologies were made on a random basis. Therefore, the modified network topologies had the same number of network nodes and the same number of physical links as the original network, but slightly different physical topologies. The details can be found in Fig.3.17 and Fig.3.18.

NSFNET and the associated modified network topologies were tested under the same total offered traffic load of 140 Erlangs. Each network had 14 nodes and 21 physical links, and was equipped with 16 wavelengths per fibre. Networks without wavelength conversion were considered throughout this chapter. Poisson traffic characteristics



were assumed. The mean lightpath request inter-arrival period was 1.3 and the mean request holding time was kept at unity value in all the cases. The non-uniformity factor was chosen at 80% of the mean request inter-arrival period to test networks with a large degree of traffic pattern variability. 25 traffic patterns based on this non-uniformity factor were randomly generated to test each network topology; hence the standard deviation of the blocking probabilities could be obtained, to give the traffic forecast tolerance of the tested network. Figures 4.1 – 4.3 show the results with both FR-FF RWA algorithm and FAR-FF RWA algorithm with 3 alternate physical routes.

It can be seen clearly from Fig.4.1 that for both FR-FF and FAR-FF algorithms, the average lightpath length showed a strong correlation with the blocking probability with uniform traffic, in that the length of the average lightpath increases with the blocking probability. This can be explained by the fact that with longer lightpaths, it is more difficult to find an available wavelength along all the physical links for that lightpath. In the wavelength-routed optical network without wavelength conversion facility, the wavelength continuity constraint and the average lightpath length are major influencing factors on the performance of the network. This phenomenon is more obvious in the case of FAR-FF algorithm, since the lightpath can be chosen from three alternate routes rather than a single fixed route, as is the case with the FR-FF algorithm. It can also be seen in Fig.4.1 that the alternate routing with disjoint-link makes the average lightpath length slightly longer than with the single fixed shortest route.

More interestingly, the result of average lightpath length versus the standard deviation of blocking probabilities, i.e. the traffic forecast tolerance, obtained with the non-uniformity factor set at 80% of the mean request inter-arrival time is shown in Fig.4.2. An approximately linear relationship can be seen for the average lightpath length and the standard deviation of blocking probabilities for the case of FAR-FF algorithm, and the average lightpath length increases with the decrease of the network's capability to accommodate traffic pattern variability. In other words, the longer the average lightpath, the lower the traffic forecast tolerance, whereas, in the case of FR-FF algorithm, this phenomenon is less obvious. However, the tendency is that the longer the average lightpath, the higher the standard deviation of the blocking probability, and hence the lower the traffic forecast tolerance.

The result of blocking probability with uniform traffic versus the standard deviation of blocking probabilities is shown in Fig.4.3. It can also be seen that for both RWA algorithms, the blocking probability with uniform traffic increases with the standard deviation of blocking probabilities. The explanation is that the lower blocking probability with uniform traffic leaves more flexibility in the network to accommodate variations of the traffic pattern. The result strengthens the findings in chapter 3 that a lower blocking probability with uniform traffic generally suggests higher robustness of the network performance to the traffic pattern changes.

In addition to the FR-FF and FAR-FF RWA algorithms, the AUR-E RWA algorithm was also employed to test the network topologies based on the original NSFNET and similar modified topologies. Due to the high computational complexity of the AUR-E algorithm, only a few of the previously modified networks were selected, at random, for this test. All other conditions were kept the same as before.

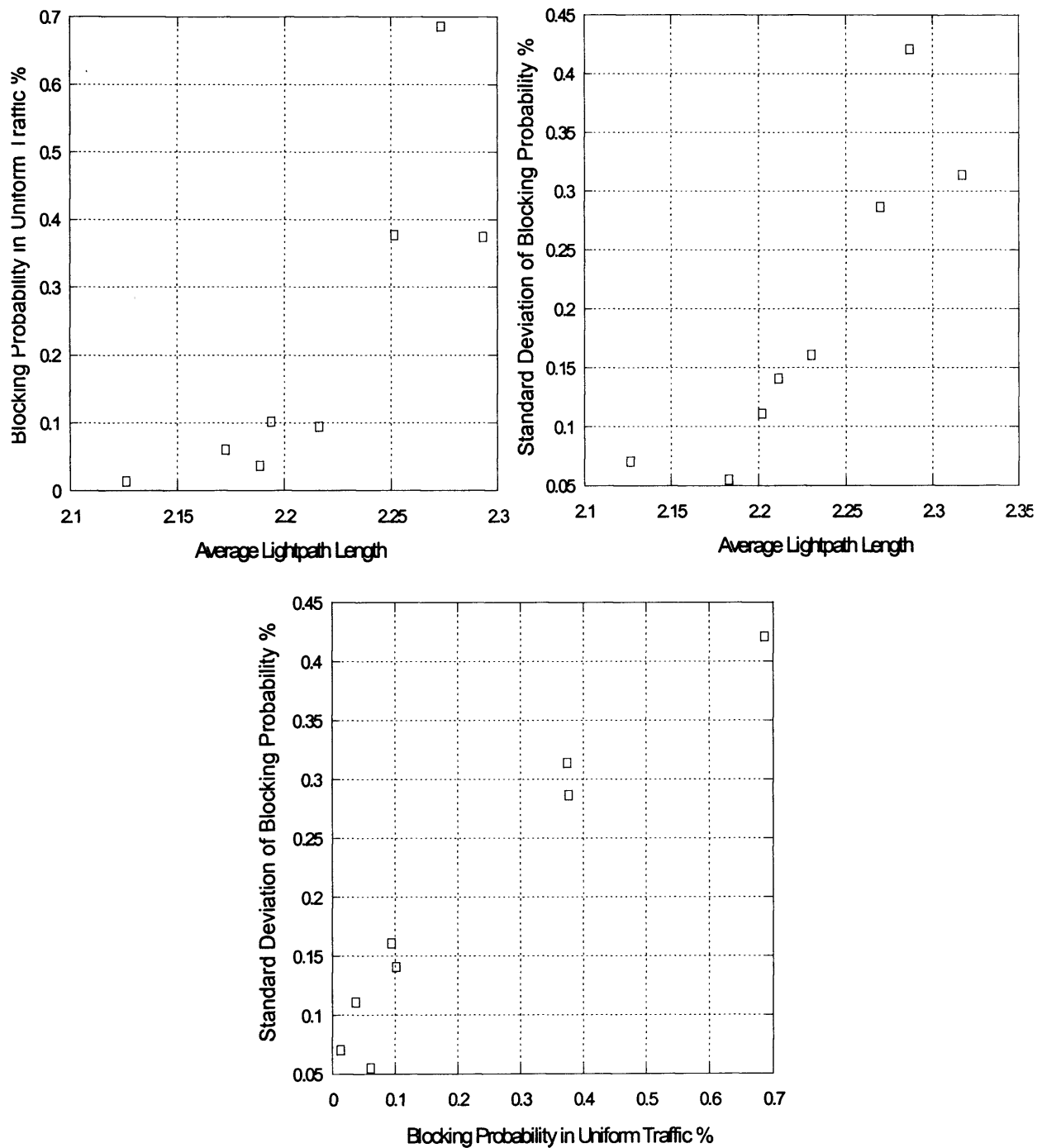


Figure 4.4 - Results for NSFNET & 1-link-difference NSFNET networks with AUR-E RWA. Upper left: average lightpath length versus blocking probability in uniform traffic; upper right: average lightpath length versus standard deviation of blocking probabilities; lower: blocking probability in uniform traffic versus standard deviation of blocking probabilities

Again, a strong relationship can be observed between the average lightpath length and the traffic forecast tolerance; the shorter the average lightpath, the higher the network tolerance to the traffic pattern variations. At the same time, low blocking probability with uniform traffic indicates high network forecast tolerance.

Another practical network, UKNET and associated modified network topologies were tested using FR-FF, FAR-FF with 3 alternate routes, and AUR-E RWA algorithms. These networks were tested with Poisson distributed lightpath requests, with the same total offered traffic load of 210 Erlangs. To maintain simplicity, the mean request inter-arrival period was 2.0 and mean request holding time was set to 1.0 in all cases. Each network had 21 network nodes and 39 physical links with each fibre equipped with 16 wavelengths. Again, the non-uniformity factor was chosen at 80% of the mean request inter-arrival period to investigate the effect of large traffic pattern variations, thereby the robustness of the network performance can be observed with the average lightpath length and blocking probability in uniform traffic.

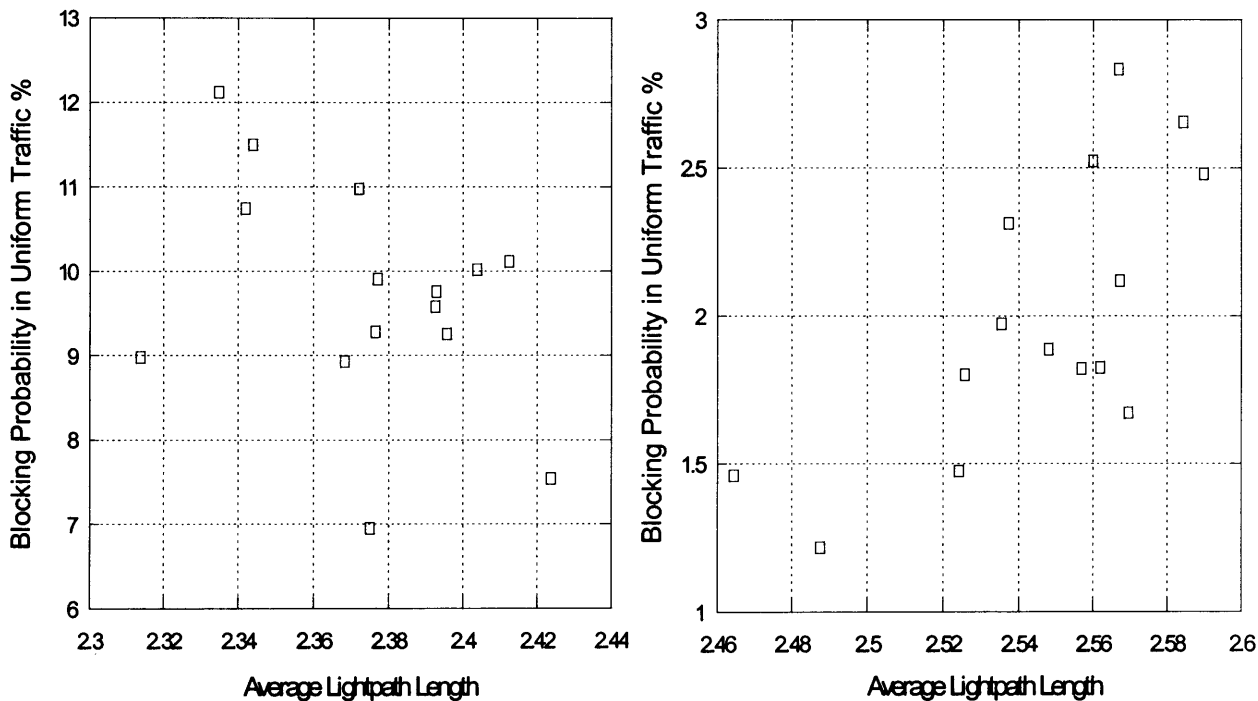


Figure 4.5 - Average lightpath length versus blocking probability in uniform traffic for UKNET & UKNET-similar Networks. Left: FR-FF algorithm; right: FAR-FF with 3 alternate paths for each node-pair.

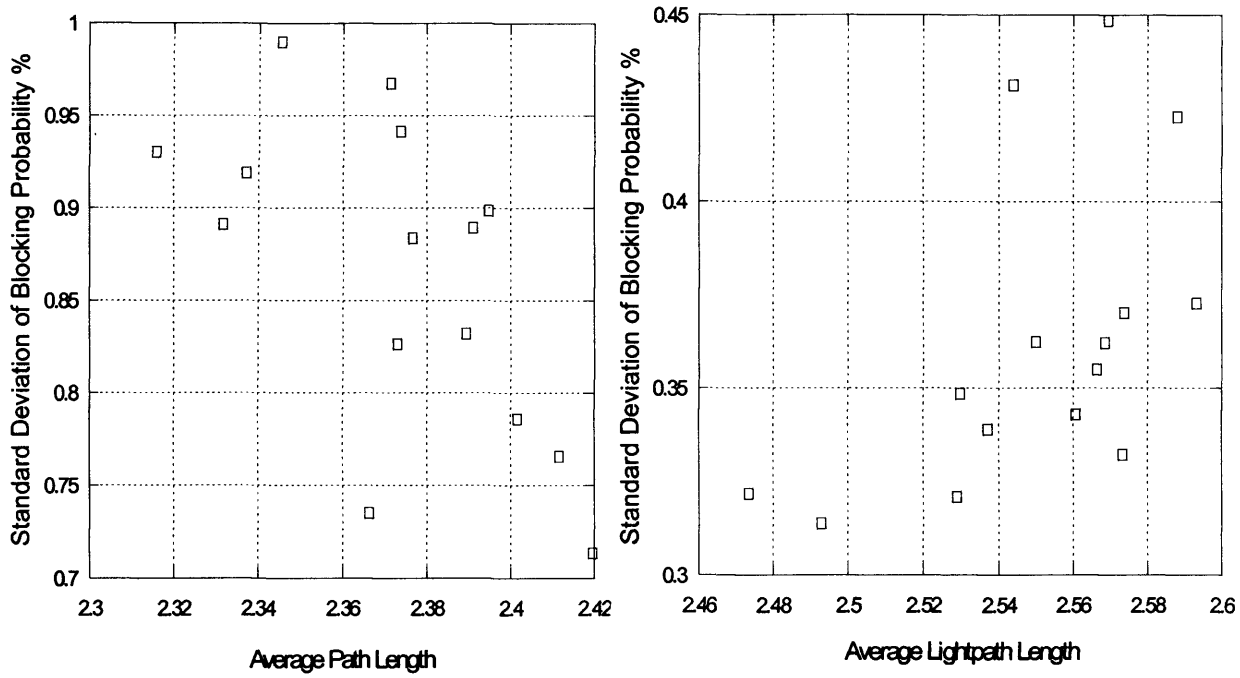


Figure 4.6 - Average lightpath length versus standard deviation of blocking probability distribution for UKNET & UKNET-similar networks (the non-uniformity is of 80% of the mean request inter-arrival period). Left: FR-FF algorithm; right: FAR-FF with 3 alternate paths for each node-pair.

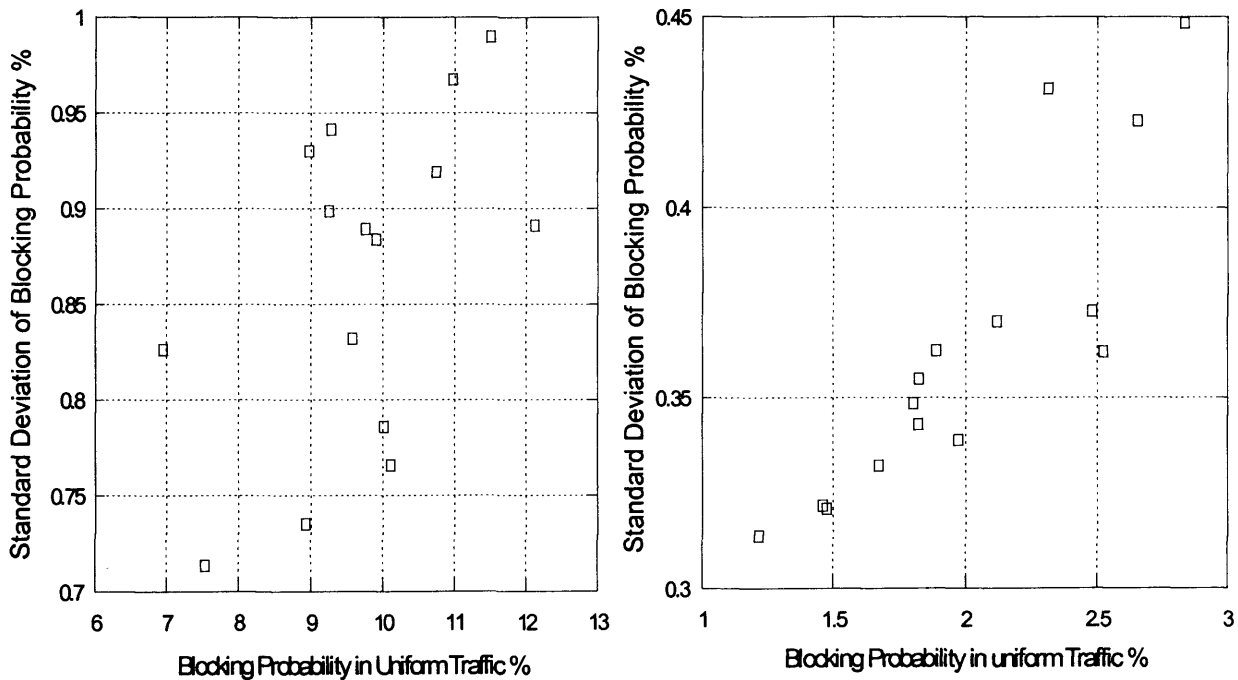


Figure 4.7- Blocking probability in uniform traffic versus standard deviation of blocking probability distribution for UKNET & UKNET-similar networks (the non-uniformity is of 80% of the mean request inter-arrival period). Left: FR-FF algorithm; right: FAR-FF with 3 alternate paths for each node-pair.

It can be clearly seen in Fig.4.5 that with uniform traffic loading, the blocking probability increases with average lightpath length in the case of FAR-FF RWA algorithm for the different modified-UKNET networks, whereas the relationship between the two parameters is not obvious in the case of FR-FF. As discussed before for the results of NSFNET and modified-NSFNET networks, the alternate routing increases the probability for a lightpath to be successfully set up, and hence becomes a major influencing factor on the network performance. However, in the case of FR-FF RWA algorithm, only one shortest path is considered for each node-pair. The average lightpath length can also be calculated theoretically as the division between the sum of the shortest path length for all the node-pairs and the number of all the node-pairs. The result in the case of FR-FF means that the average lightpath length considering only one single shortest path for each node-pair does not show a significant correlation with the blocking probability with uniform traffic.

The same phenomenon can be observed in Fig.4.6 for the case of FR-FF algorithm, in that the average lightpath length does not show any obvious correlation with the standard deviation of blocking probabilities. On the contrary, the average lightpath length shows a strong relationship with the standard deviation of blocking probabilities with the FAR-FF RWA algorithm, which means that the networks with lower average lightpath lengths have higher traffic forecast tolerance than networks with longer average lightpaths.

Furthermore, it can be observed from Fig.4.7 that, regardless of the RWA algorithm, the blocking probability with uniform traffic shows a strong relationship with the standard deviation of the blocking probabilities. As discussed above, the lower blocking probability with uniform traffic gives the network more flexibility to tolerate unpredictable traffic pattern changes. It should also be noted that the relationship is less obvious in the case of the FR-FF algorithm than in the case of the FAR-FF algorithm.

As with the topologies based on NSFNET, the UKNET and modified-UKNET networks were then tested with the AUR-E RWA algorithm, to investigate the dependence of the traffic forecast tolerance on average lightpath length with this algorithm. All other parameters were kept the same. Similar results were found as

with the modified-NSFNET topologies, however the average lightpath length was found to slowly increase with the blocking probability with uniform traffic loading and standard deviation of the blocking probabilities for the majority of the network topologies tested. Only four of the modified networks showed a significant increase in both these parameters with increasing average lightpath length. In addition, an approximately linear relationship between the blocking probability with uniform traffic loading and the standard deviation of the blocking probabilities was observed. These findings are consistent with the results from the modified-NSFNET topologies.

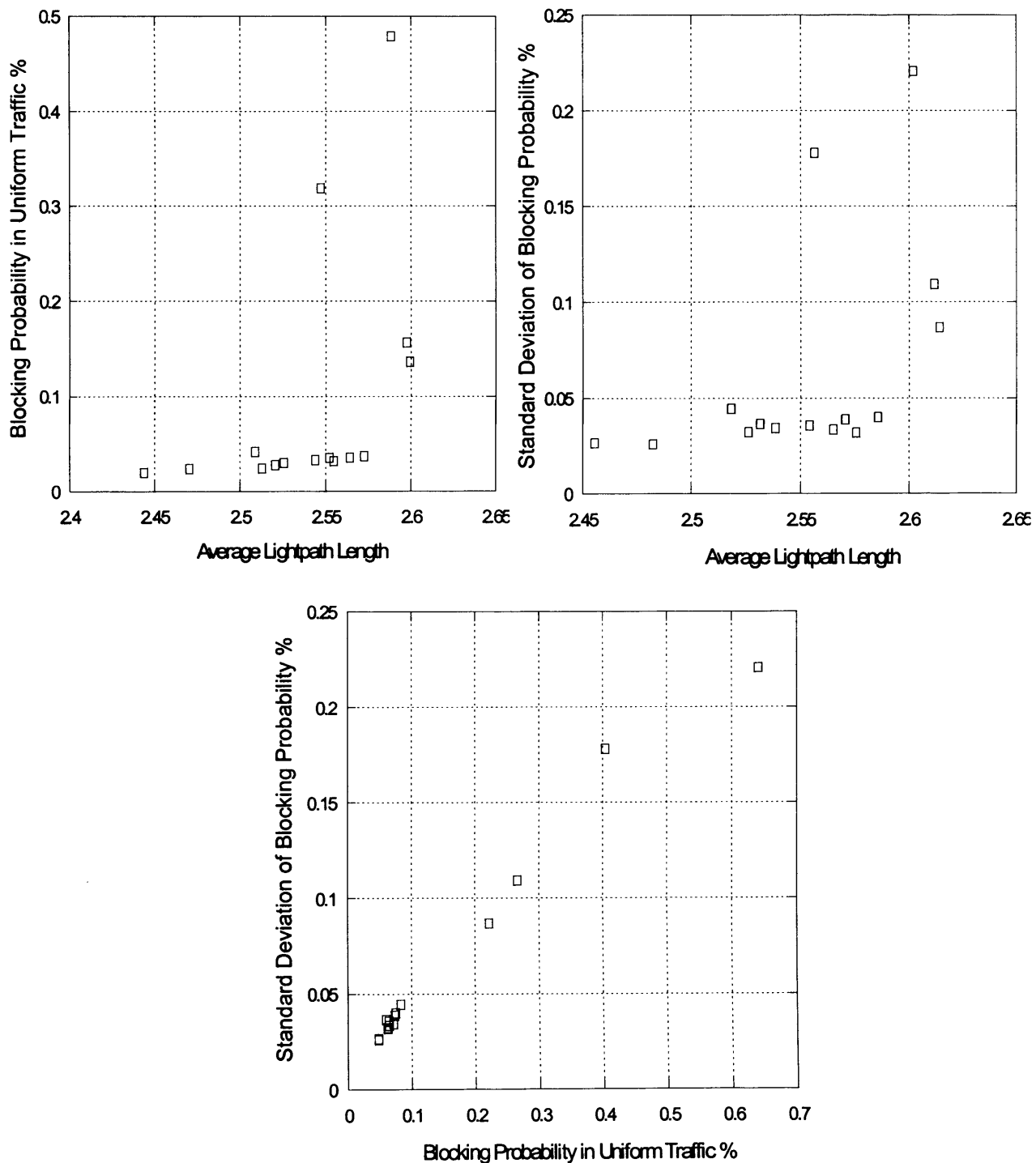


Figure 4.8 - Results for UKNET & UKNET-similar networks with AUR-E RWA.

Upper left: average lightpath length versus blocking probability in uniform traffic;  
 upper right: average lightpath length versus standard deviation of blocking probabilities;  
 lower: blocking probability in uniform traffic versus standard deviation of blocking probabilities

Another randomly connected network (Fig.3.5.) with an associated series of modified network topologies with 1-link-difference were tested for the same three RWA algorithms. These networks have 15 nodes and 31 physical links with 8 wavelengths equipping each fibre. The total offered traffic load of 87.5 Erlangs was kept the same for all networks. Poisson traffic statistics were used with mean lightpath request inter-arrival time of 2.4 and mean request holding time of 1.0 for all cases. Again, the non-uniformity factor was chosen at 80% of the mean request inter-arrival period to assess the performance of networks with large variations in traffic load distribution. Results for the randomly connected network are shown in Figures 4.9 – 4.12.

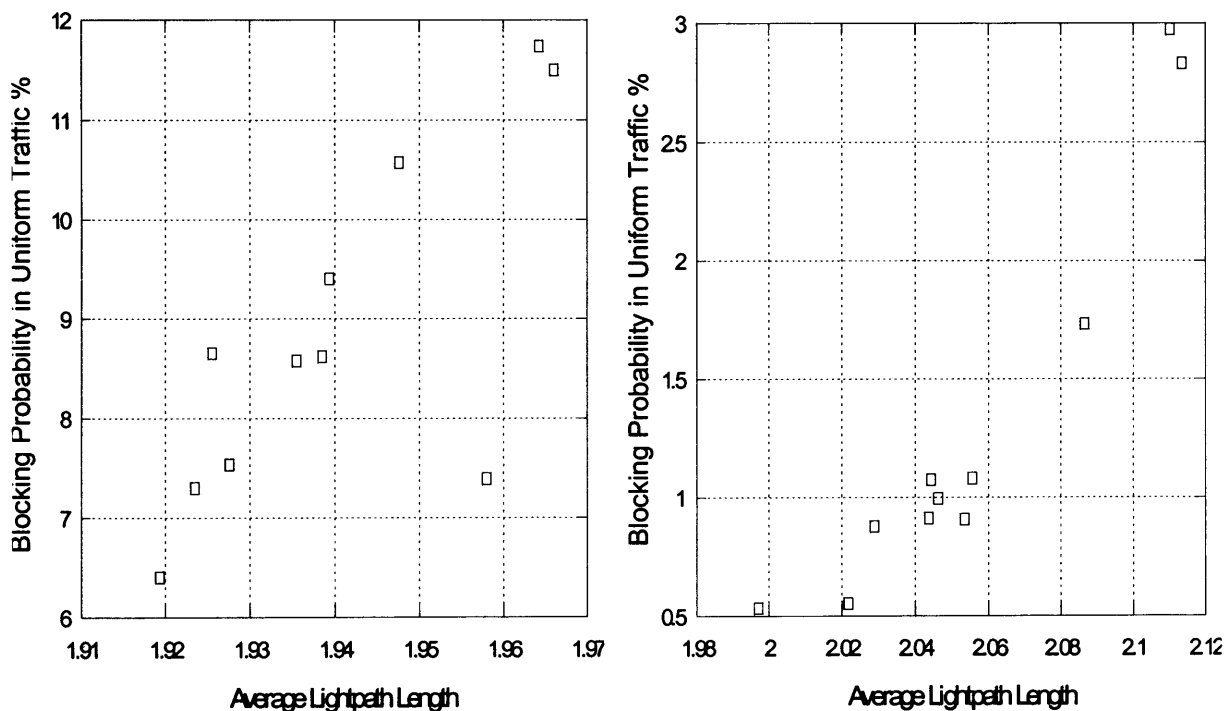


Figure 4.9 - Average lightpath length versus blocking probability in uniform traffic for RANET & RANET-similar networks. Left: FR-FF algorithm; Right: FAR-FF with 3 alternate paths for each node-pair.



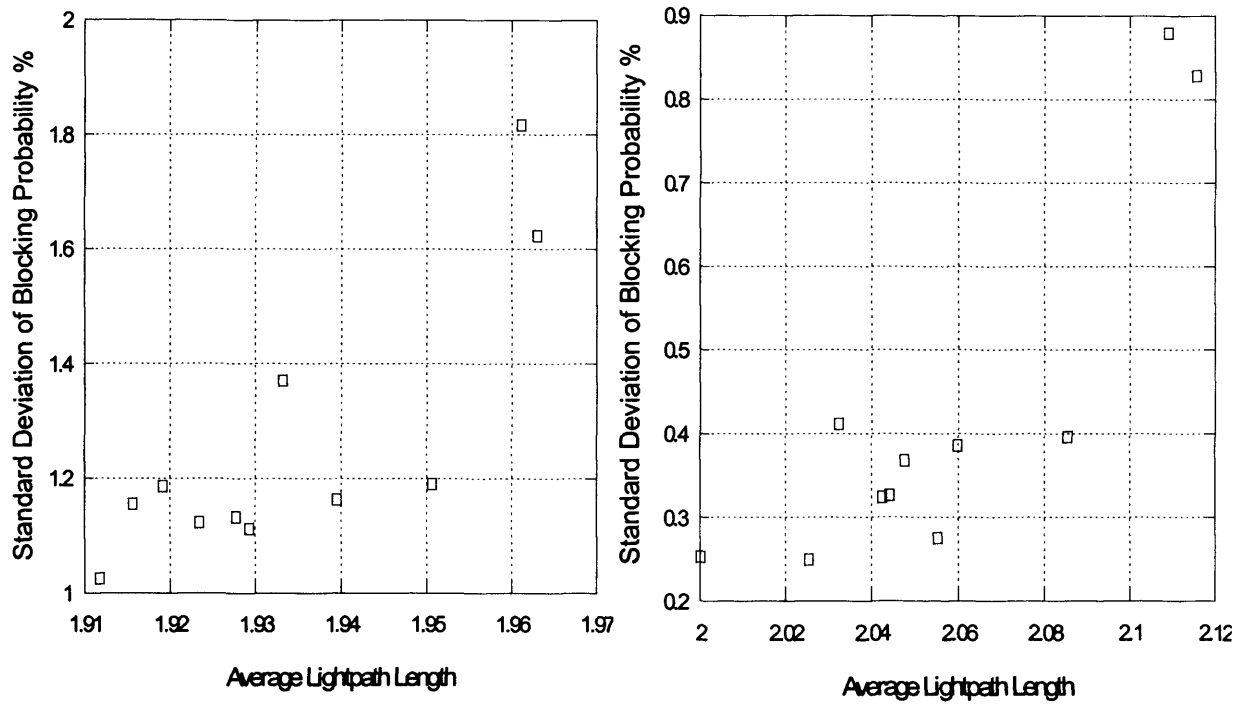


Figure 4.10 - Average lightpath length versus standard deviation of blocking probability distribution for RANNET & RANNET-similar networks (the non-uniformity is of 80% of the mean request inter-arrival period). Left: FR-FF algorithm; right: FAR-FF with 3 alternate paths for each node-pair.

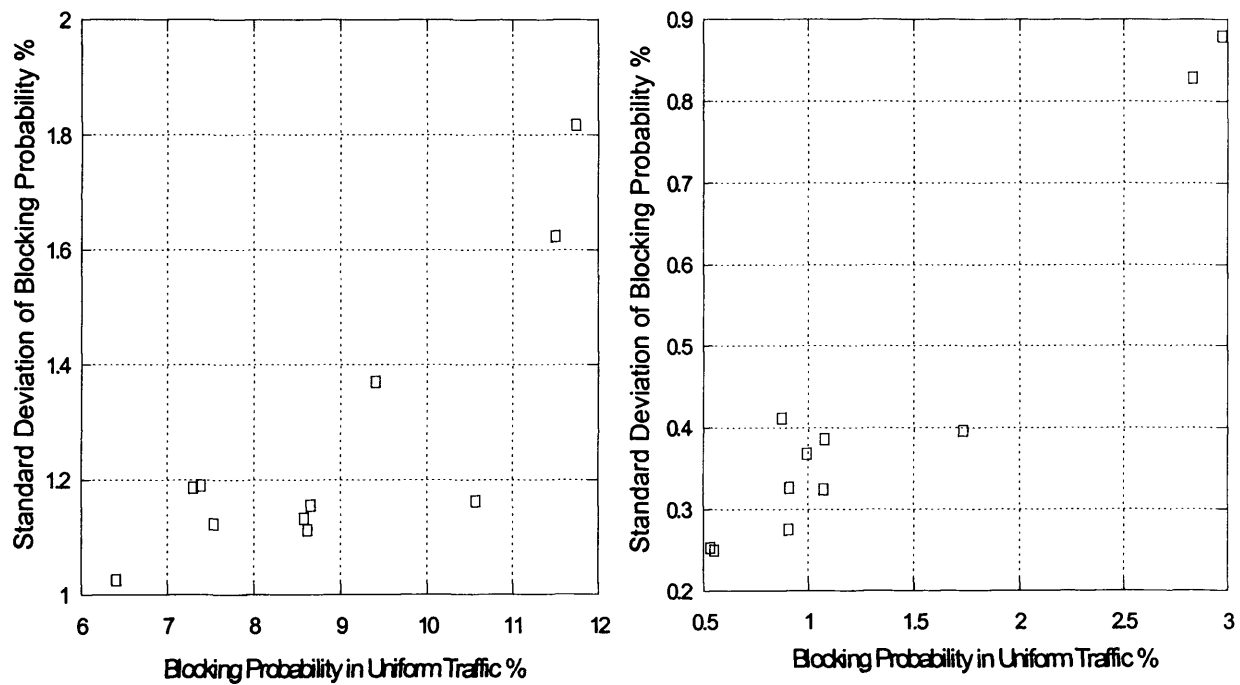


Figure 4.11 - Blocking probability in uniform traffic versus standard deviation of blocking probability distribution for RANNET & RANNET-similar networks (the non-uniformity is of 80% of the mean request inter-arrival period). Left: FR-FF algorithm; Right: FAR-FF with 3 alternate paths for each node-pair.

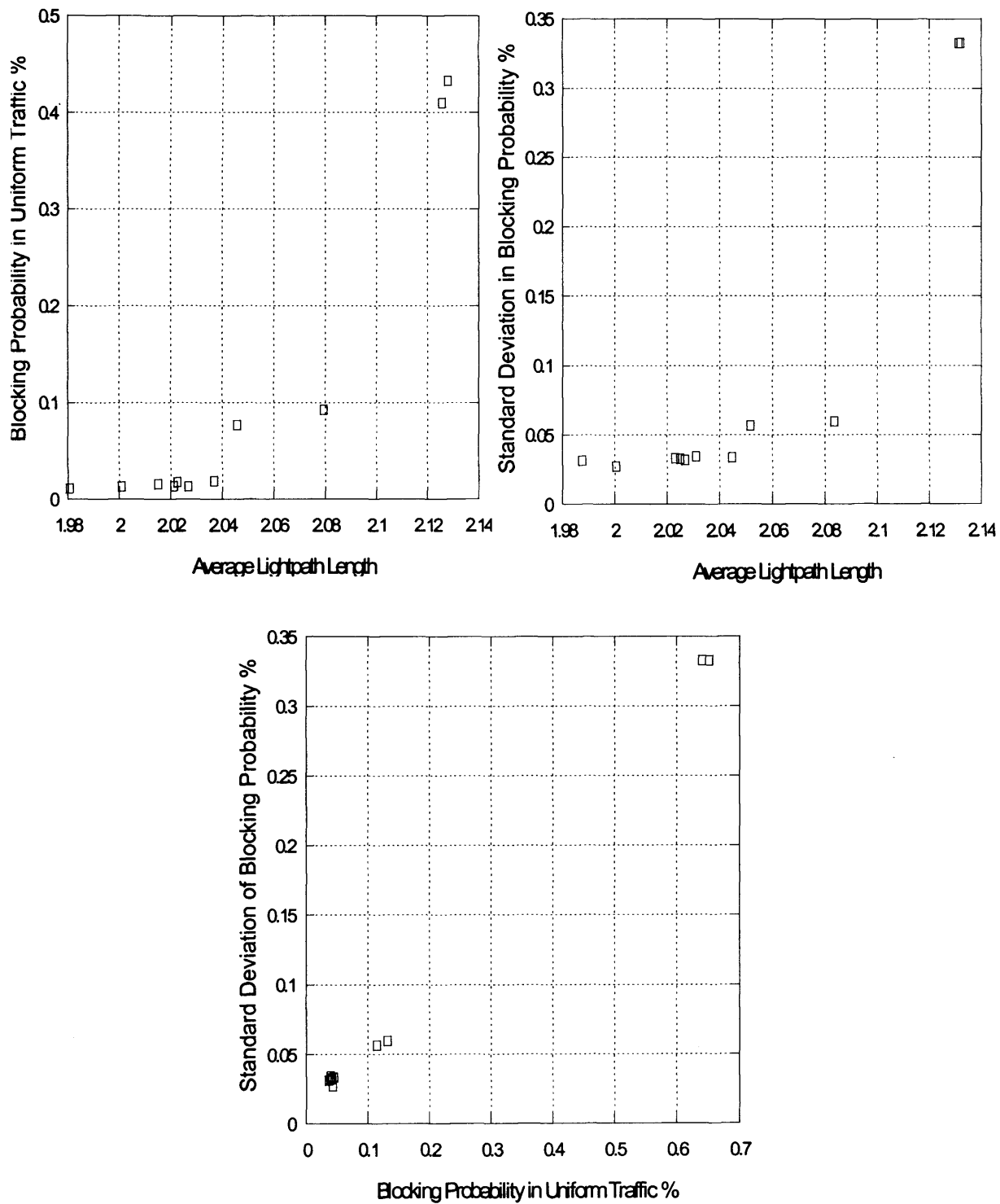


Figure 4.12 - Results for RANNET & RANNET-similar networks with AUR-E RWA. Upper left: average lightpath length versus blocking probability in uniform traffic; upper right: average lightpath length versus standard deviation of blocking probabilities; lower: blocking probability in uniform traffic versus standard deviation of blocking probabilities

The results for modified-RANNET networks show consistency with the previous results obtained for NSFNET- and UKNET-based topologies. The average lightpath length shows a tendency of increasing with both the blocking probability with uniform traffic loading and the standard deviation of blocking probabilities with a high non-uniformity factor for all three RWA algorithms. Unlike with the modified-UKNET networks, there was no large discrepancy in the results between the FR-FF algorithm and FAR-FF algorithm. In addition, the blocking probability with uniform traffic and the standard deviation show an approximately linear relationship with the AUR-E RWA algorithm.

In summary, the results for three types of networks give a number of important conclusions. First of all, the network traffic forecast tolerance is dependent on the average lightpath length, with shorter average lightpaths indicating the network has a higher tolerance to traffic pattern variations. However, a discrepancy was observed with different RWA algorithms, especially when the RWA algorithm only considers one shortest path when setting up each lightpath. This can be seen by comparing the results of FAR-FF and AUR-E RWA algorithms with the FR-FF algorithm, as both of the former algorithms consider more than one shortest physical path when setting up each lightpath. In fact, AUR-E picks the shortest path among all the possible physical routes between the source and destination nodes. This suggests that the calculation of the average lightpath length for the whole network including more physical routes for each node-pair gives a more accurate prediction of the network robustness to traffic pattern variations. Furthermore, the results indicate that designing the network with shorter a average lightpath length gives the network a higher tolerance to traffic pattern variability. This is discussed and further proven in Section 4.4. Secondly, for all the network topologies tested, regardless of the RWA algorithm used, the blocking probability with uniform traffic gives a reliable prediction of the network's traffic forecast tolerance, i.e. the standard deviation of blocking probability with non-uniform traffic loading.

### 4.3 Wavelength Requirements in Static WRONs, and their Correlation with Traffic Forecast Tolerance

Besides the average lightpath length, another important parameter, the number of wavelengths required to fully interconnect all the network nodes (referred to as the wavelength requirement) which is strongly dependent on the physical topology of the network, was investigated.

#### 4.3.1 Introduction of Wavelength Requirement in Static WRONs

As explained in chapter 2, optical transport networking is migrating from static architectures to a more flexible infrastructure which satisfies the demands resulting from the new dynamic nature of the traffic. However, the research work carried out in the area of static wavelength-routed optical networks is still useful in assessing the performance of dynamic wavelength-routed optical networks.

In the case of high-capacity transport optical networks, where lightpaths provide quasi-static pipes and in which no blocking is allowed, the number of wavelengths,  $N_\lambda$ , required to interconnect the network nodes and satisfy a pre-assigned traffic demand is especially important, since  $N_\lambda$  directly determines the network design parameters and device configuration. This kind of optical network architecture is considered to be static or quasi-static, because the established lightpaths last for days, months, and even years. The established lightpaths are seldom reconfigured, and hence are regarded as static.

The wavelength requirement in static wavelength-routed optical network can be explained by the simple network schematics in Fig.4.13. Any arbitrarily-connected network topology is composed of  $N$  nodes and  $L$  links. It is assumed that each link consists of a single bi-directional fibre. This is the worst case for the wavelength requirement, as multiple fibres per link result in numerous disjoint physical paths, and therefore, smaller  $N_\lambda$ . Another assumption is made that the minimum number of fibres incoming and outgoing any node, often referred as the nodal degree, is  $\delta_{\min} = 2$ . This is due to the fundamental requirement for network reliability, so that in

the case of a single link failure, the network node still remains connected with other network parts. Hence, restoration lighpaths can be established using other physical links connected with the corresponding network node.

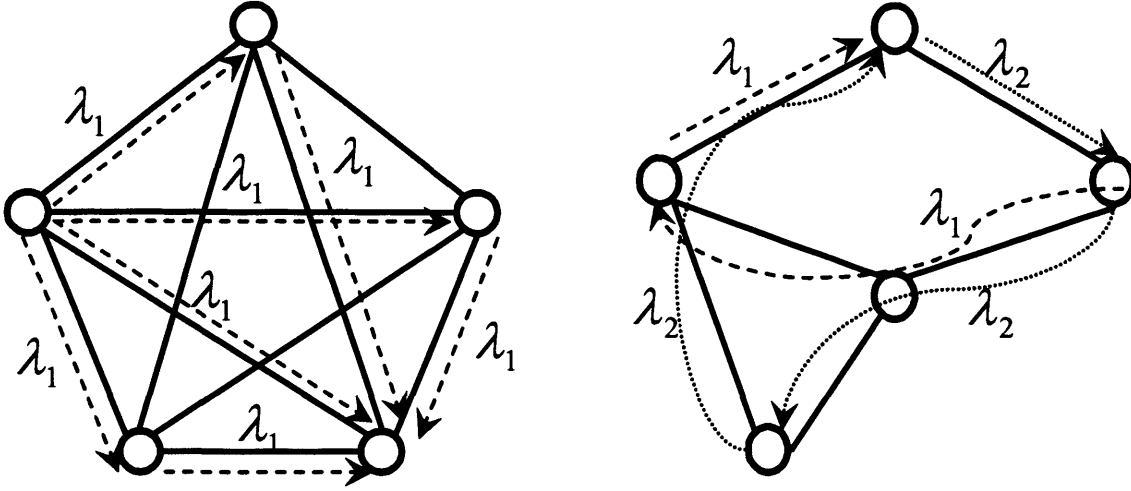


Figure 4.13 - Left: fully-connected network with  $\alpha = 1$  ; Right: example of 5-node 6-link arbitrarily-connected network with  $\alpha = 0.6$

A parameter, referred to as the network physical connectivity, was introduced to characterise the physical network topology [Bar96]:

$$\alpha = \frac{L}{L_{FC}} = \frac{2L}{N(N-1)} \quad (4.6)$$

$\alpha$  is the ratio between the number of network links and the number of links,  $L_{FC}$ , that is needed to fully connect the network. A network is described as fully-connected when there is a distinct link from every network node to every other network node

(Figure 4.13 Left). Hence,  $L_{FC} = \frac{N(N-1)}{2}$ . It is also easy to understand that if there

are  $\frac{N(N-1)}{2}$  links, there exists only one topological layout for the network, since

any extra link to connect any two network nodes is redundant. In addition, it is assumed that any network has a minimum nodal degree  $\delta_{\min} = 2$ , which gives the least connected network topology, the ring topology. Therefore, the range of the

physical connectivity for any network is  $\frac{2}{N-1} < \alpha \leq 1$ .

It is clear that, for any fully-connected network, only one wavelength is required to establish lightpaths for all node-pairs, as this specific wavelength can be re-used in each different physical link outgoing from any network node, since the node is connected to every other node. However, in an arbitrarily-connected network with a number of links lower than  $L_{FC}$ , a single wavelength is not sufficient to establish lightpaths connecting all node-pairs. Some of the lightpaths have to share the same physical links in this case. Hence more wavelengths are needed to connect node-pairs in order to avoid wavelength collisions. This is illustrated in Fig.4.13 (right). Therefore, it is intuitively obvious that the more physical links the network has, the lower the number of distinct wavelengths that are required to interconnect all the network node-pairs.

The major contribution made by [Bar96] is the investigation of the relationship between the physical connectivity and wavelength requirement for the static wavelength-routed network. It was found that networks with larger physical connectivity value show lower wavelength requirement than other networks of the same size (same number of  $N$ ) with lower physical connectivity. Essentially, it is because the networks with larger physical connectivity value have relatively more physical links than networks of the same size with smaller physical connectivity value.

Since different arrangements for the lightpaths may lead to different maximum aggregate number of distinct wavelengths on a given network topology, a smaller maximum aggregate number of distinct wavelengths are desirable in order to save the cost on network dimensioning. Therefore, the key issue is to connect the given network topology optimally by arranging lightpaths for node-pairs, so that the smallest number of distinct wavelengths can be found.

To reach the optimal lightpath arrangement for any given network is actually to carry out the routing and wavelength allocation (RWA) decision in an optimised way for the network. It should be noted that the RWA problem in static wavelength-routed optical network is different to that of the dynamic wavelength-routed optical network.

### 4.3.2 Calculation of Wavelength Requirement in a Static Network

As described in Section 4.3.1, the wavelength requirement  $N_\lambda$  can be derived by solving the routing and wavelength allocation problem, that is, optimally routing and assigning the wavelengths for a given set of connection requests onto a given physical topology. It is well known that the RWA problem in static wavelength-routed optical networks is an NP-complete problem [Gon86], implying that only small networks may be optimally designed, and is subject to available computational resources.

Hence, several methods have been proposed to solve the RWA problem in static wavelength-routed optical network in order to obtain the wavelength requirement  $N_\lambda$ . The proposed methods include integer linear program (ILP) formulations, heuristic algorithms, and manual inspection with network physical upper and lower bounds.

In general, ILP problems are optimisation problems involving a finite number of integer variables, in which a linear function is minimised or maximised, subject to a set of linear equations or constraints on the variables [Hu70]. ILP formulation can be used for the solution of the RWA problem aiming at minimising the wavelength requirement. It is an analytical method to calculate the wavelength requirement. Many studies have been carried out using ILP to solve the RWA problems, the major contributions including [Bar94][Ram95][Cae97][Ban96][Wau96]. However, the ILP formulation for RWA problems inherits the generic ILP NP-complete nature. It is well known that the ILP formulations for RWA problems are computationally difficult [Bie95], given the large number of variables and constraints required. The limitations of ILP formulations restrict the general solutions for RWA problems on any network topologies. Most of the analytical methods are only suitable for small networks.

To avoid the limitations of ILP formations, some near-optimal heuristic algorithms have been proposed to solve the RWA problem. Major contributions include [Bar96][Nag95][Hun98][Jag95][Hun97]. The heuristic algorithm proposed in [Bar96] is used in this work to obtain the static network wavelength requirement for the dynamic wavelength-routed optical network. The algorithm solves the routing and wavelength allocation sub-problems separately.

First, physical paths are assigned to all node-pairs in the network. The minimum number of hops algorithm is employed so that each lightpath uses the minimum number of physical links. In addition, longer physical paths may be used instead of the shortest physical paths to enable more efficient lightpath allocation, and, hence, reduce  $N_\lambda$ . Furthermore, node-pairs with the largest minimum number of hops are assigned wavelengths first. Since a path set exists for each node-pair, a certain degree of freedom can be achieved to allocate the lightpaths among the network links as evenly as possible, in order to minimise the link congestion. Secondly, the wavelengths are then assigned to the paths (assuming the network does not have wavelength conversion facility). The paths are ranked in order of decreasing length, and the longest ones are assigned wavelengths first, since long paths are harder to allocate due to the difficulty of finding a unique free wavelength on a large number of physical links. The highest wavelength assigned amongst all node-pairs determines the network wavelength requirement  $N_\lambda$ . A formal description of the algorithm is given in Appendix B from [Bar96].

Besides the analytical and heuristic methods, the physical lower bound and upper bound for  $N_\lambda$  are also proposed in [Ajm93][Nag95][Bar96]. These studies help to understand the extreme cases for static case wavelength requirement from a perspective of network physical features.

Proposed in [Ajm93] and referred to as the distance bound in [Wis96], a lower bound on the wavelength requirement  $N_\lambda$  was obtained. The minimum total number of links occupied by all the network lightpaths is defined as

$$L_T = \sum_{z \in Z} m(z) \quad (4.7)$$

where  $Z$  is the whole set of node-pairs for the network,  $m(z)$  is the minimum distance in terms of links for each node-pair  $z$  in the node-pair set  $Z$ . An ideal allocation of the lightpaths, evenly distributed over the  $L$  network links, would lead to a wavelength requirement equal to [Ajm93]

$$W_{DB} = \left\lceil \frac{L_T}{L} \right\rceil \quad (4.8)$$



where  $\lceil x \rceil$  represents the lowest integer greater than or equal to  $x$ .  $W_{DB}$  can be easily found once the minimum number of links for all the node-pairs is obtained.

Another lower bound for  $N_\lambda$  was proposed in [Nag95] and is referred to as the partition bound in [Wis96] (also referred to as the limiting cut in [Bar96]). To obtain the partition bound, a network cut is considered which divides the network topology into two parts. The network cut can be regarded as a subset of links  $C$  which belongs to the whole network physical link set  $A$  ( $C \subset A, C \neq \Phi, C \neq A$ ), whose elimination results in two disjoint subsets of network nodes,  $S$  and  $N \setminus S$  respectively. The total number of lightpaths traversing the network cut  $C$  is

$$D_C = \sum_{z \in \gamma(C)} d(z) \quad (4.9)$$

where  $d(z)$  is the demand in number of bi-directional lightpaths for node-pair  $z$ , and  $\gamma(C) = \{(z_1, z_2) \in Z \mid z_1 \in S, z_2 \in N \setminus S\}$ . Formula 4.9 can be simplified and written as  $D_C = |S| \cdot |N \setminus S|$ . It is straightforward to derive the minimum number of distinct wavelengths necessary to satisfy the traffic demand across the network cut  $C$ , since it is the division between the number of lightpaths travelling across the network cut and the number of links in the network cut  $C$ .

$$W_C = \left\lceil \frac{D_C}{|C|} \right\rceil \quad (4.10)$$

where  $|C|$  is the number of links in the network cut  $C$ . It is obvious that different network cuts within the network result in different values of  $W_C$ , and the largest one determines the lower limit  $W_{PB}$

$$W_{PB} = \max_{C \subset A} W_C = \max_{C \subset A} \left\lceil \frac{|S| \cdot |N \setminus S|}{|C|} \right\rceil \quad (4.11)$$

It is pointed out in [Bar96] that for a given network topology, the larger value of  $W_{DB}$  and  $W_{PB}$  determines the actual physical lower bound  $W_{LB}$  on the static network wavelength requirement,

$$W_{LB} = \max(W_{DB}, W_{PB}) \quad (4.12)$$

It is shown in [Bar96] that, in practical networks, the partition bound sets the lower limit on  $N_\lambda$ . Conversely, in random networks with large size  $N$ , the lower limit is governed by the distance bound [Wis96].

These theoretical bounds show that  $N_\lambda$  is governed by the physical topology of the network, and hence can be regarded as one of the physical attributes of any network topology.

### 4.3.3 Static Case Wavelength Requirement with Practical and Randomly Connected Networks

As discussed in Section 4.3.2, the wavelength requirement in static operation,  $N_\lambda$ , can be regarded as important physical attributes of any network topology. In this section, studies are carried out to further investigate the relationship between physical features of network topology and traffic forecast tolerance of the network. In particular, the value of  $N_\lambda$  and the robustness of the network performance.

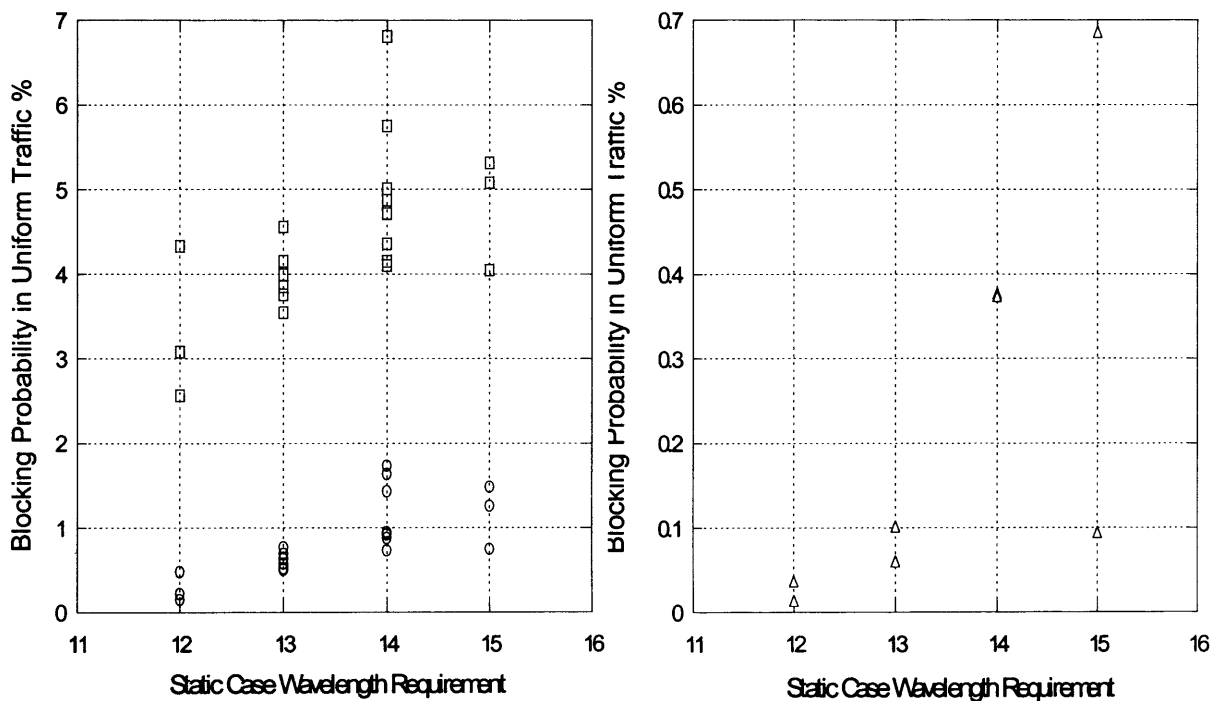


Figure 4.14 - Static case wavelength requirement versus blocking probability in uniform traffic for NSFNET & NSFNET-similar networks. Left: FR-FF (squares) and FAR-FF with 3 alternate paths (circles); right: AUR-E

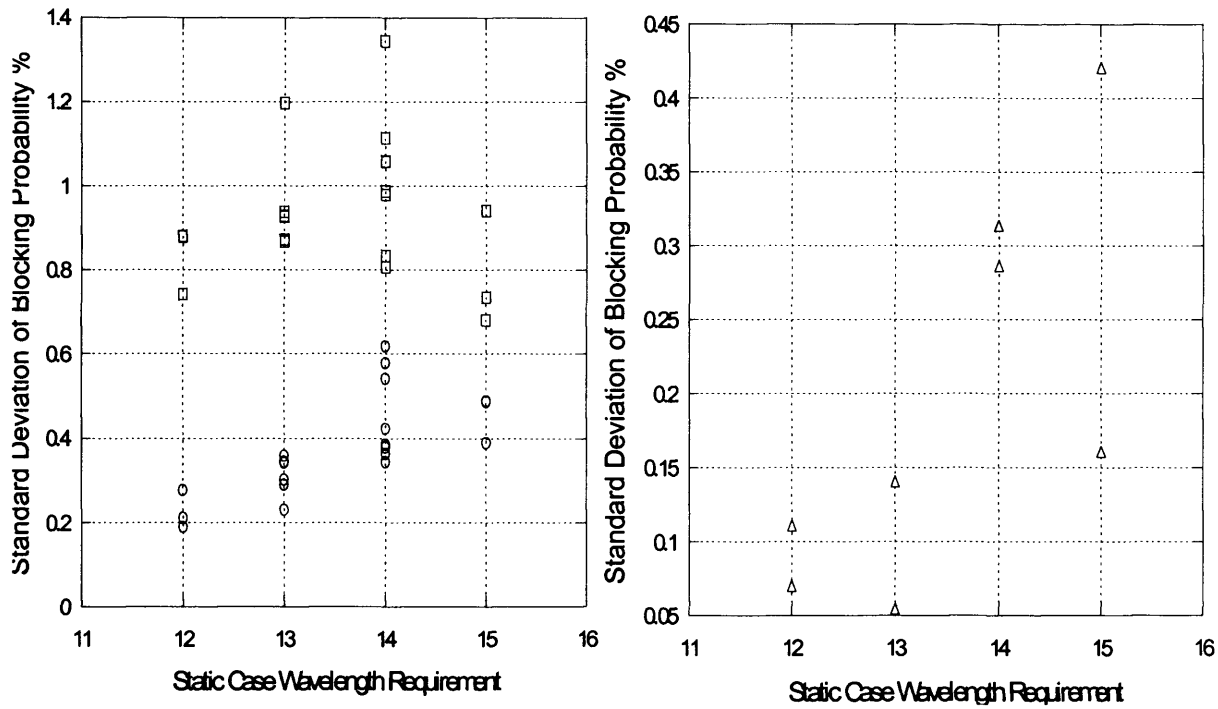


Figure 4.15 - Static case wavelength requirement versus standard deviation of blocking probabilities for NSFNET & NSFNET-similar networks (the non-uniformity factor is of 80% of the mean request inter-arrival period). Left: FR-FF (squares) and FAR-FF with 3 alternate paths (circles); right: AUR-E

Calculations of the wavelength requirement,  $N_\lambda$ , are carried out on the same networks as tested previously in assessing the relationship between average lightpath length and traffic forecast tolerance. The results for NSFNET and its related modified networks are shown in Figure 4.14 – 4.15. All the simulation parameters were kept the same as in the previous section. It can be clearly seen that both the blocking probability with uniform traffic and the standard deviation of blocking probabilities at high non-uniformity factor increase with the wavelength requirement in static operation,  $N_\lambda$ , regardless of the RWA algorithm used. The results imply that, in general, the networks with larger wavelength requirement to fully interconnect the nodes in static operation exhibit lower traffic forecast tolerance. However, some discrepancies can be observed, as a few of the networks show a high wavelength requirement but have a relatively low blocking probability with uniform traffic and a low standard deviation of blocking probability. These networks need to be further investigated.

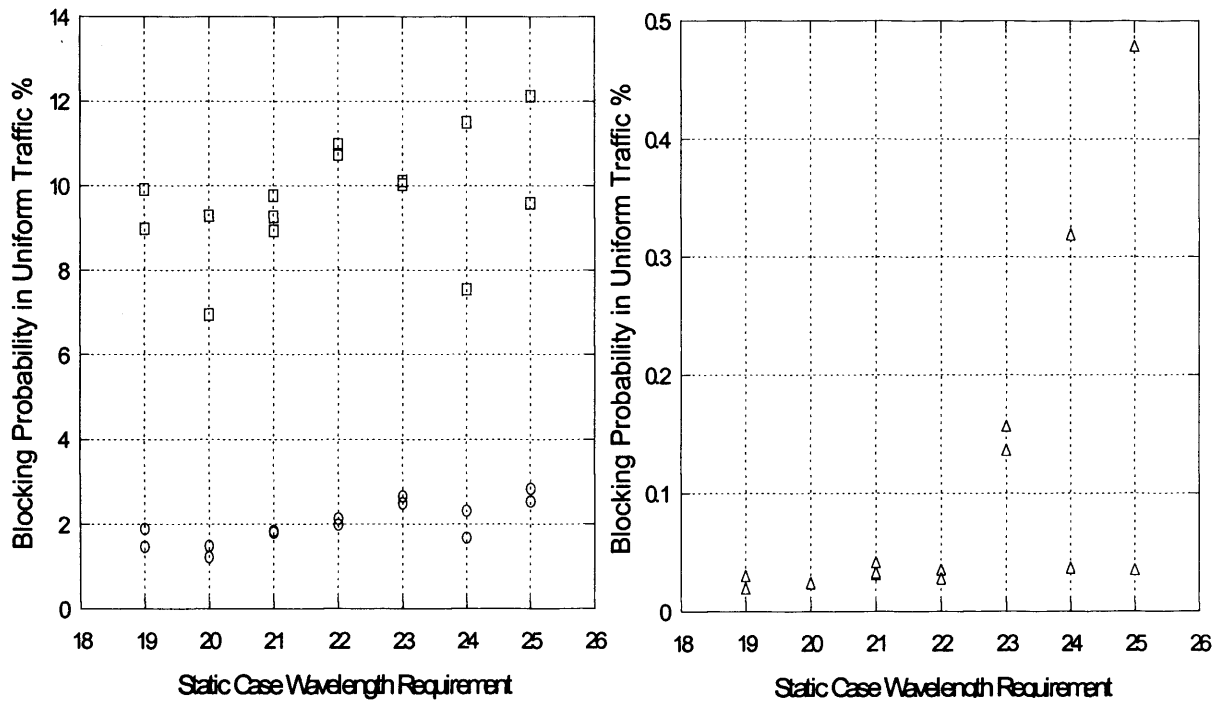


Figure 4.16 - Static case wavelength requirement versus blocking probability in uniform traffic for UKNET & UKNET-similar networks. Left: FR-FF (squares) and FAR-FF with 3 alternate paths (circles); right: AUR-E

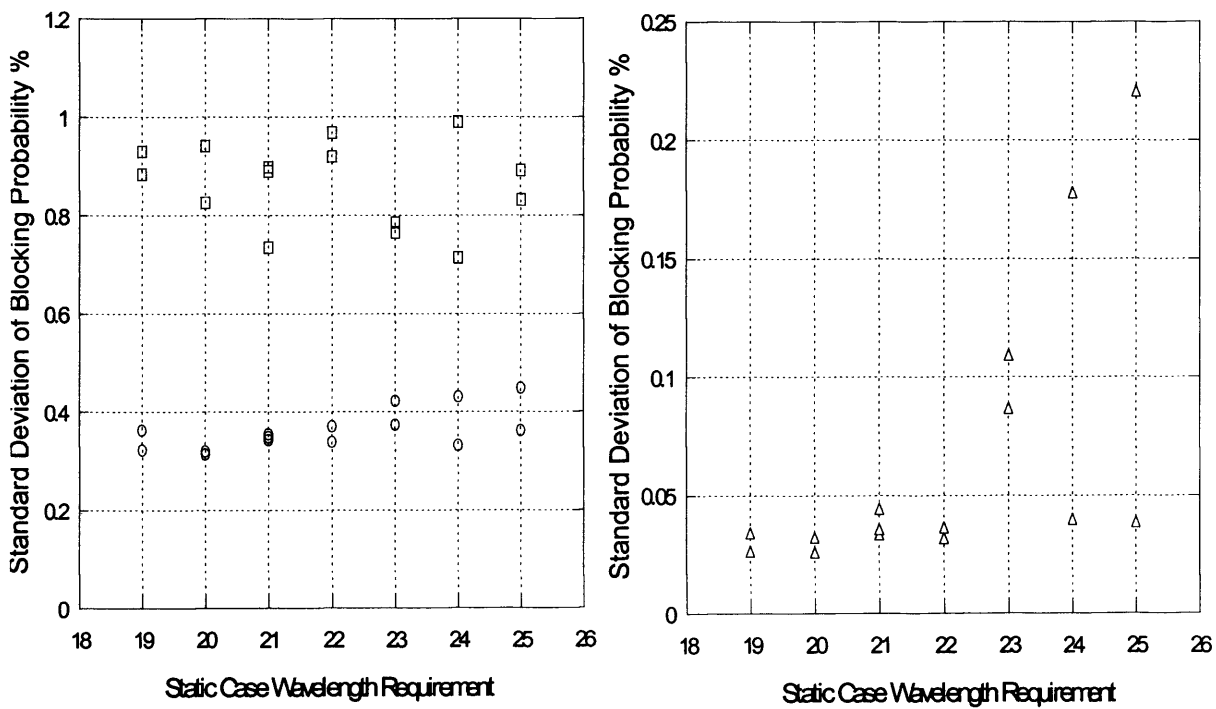


Figure 4.17 - Static case wavelength requirement versus standard deviation of blocking probabilities for UKNET & UKNET-similar networks (the non-uniformity

factor is of 80% of the mean request inter-arrival period). Left: FR-FF (circles) and FAR-FF with 3 alternate paths (squares); right: AUR-E

The static case wavelength requirement was next calculated for the modified-UKNET topologies; as before, this was then compared with the blocking probability performance both with uniform traffic and with large traffic pattern variations. Similar results were found with those for the modified-NSFNET topologies. Both the blocking probability with uniform traffic and the standard deviation of the blocking probabilities with a large traffic non-uniformity factor increase with the static case wavelength requirement, regardless of the RWA algorithms, although, as in the case of the modified-NSFNET topologies, a few irregular cases can be observed, where a higher wavelength requirement does not necessarily mean a lower forecast tolerance.

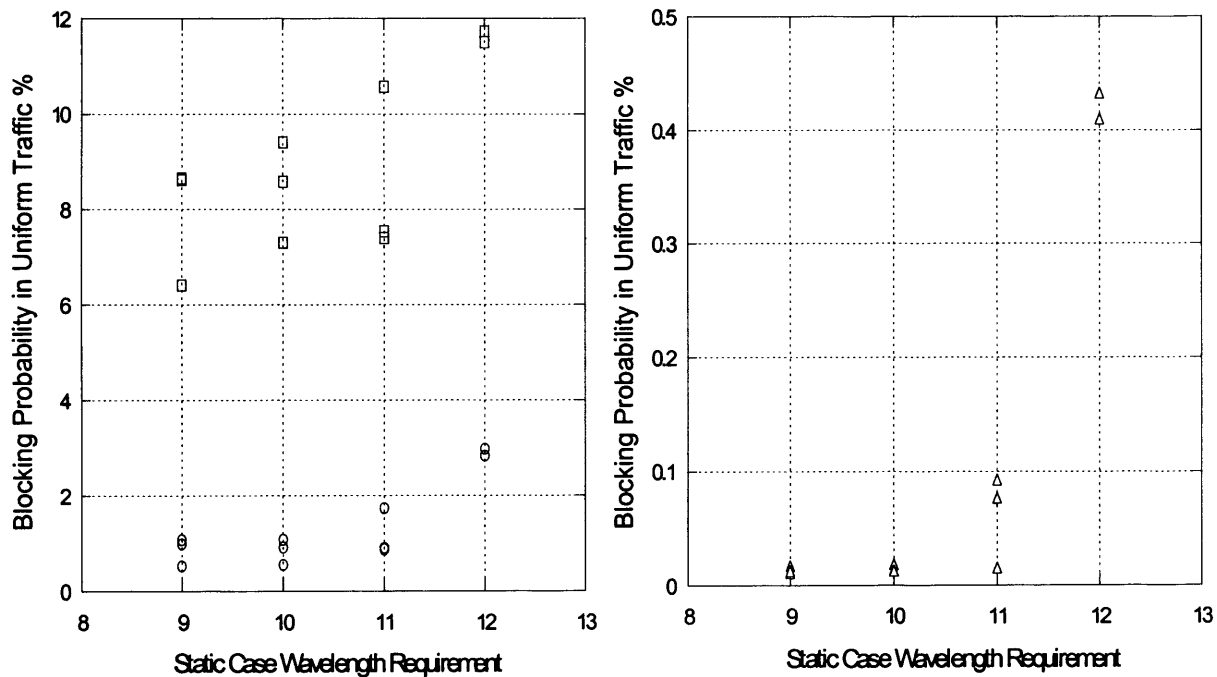


Figure 4.18 - Static case wavelength requirement versus blocking probability in uniform traffic for RANNET & RANNET-similar networks. Left: FR-FF (squares) and FAR-FF with 3 alternate paths (circles); right: AUR-E

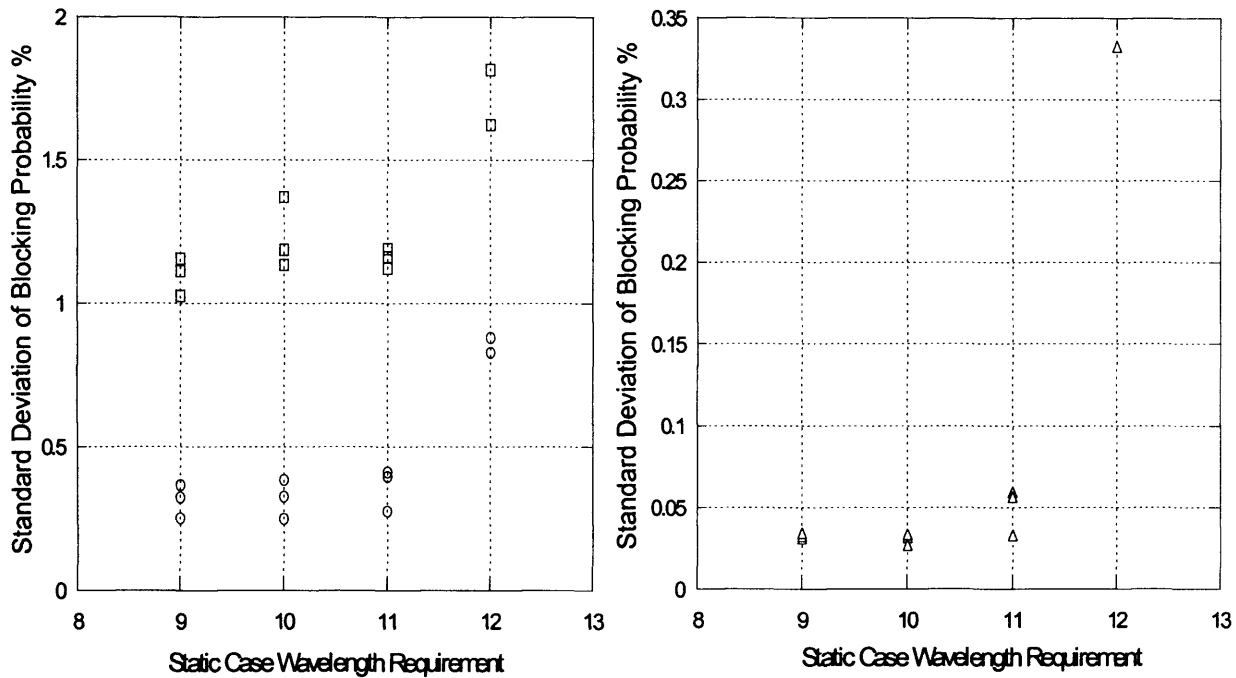


Figure 4.19 - Static case wavelength requirement versus standard deviation of blocking probabilities for RANNET & RANNET-similar networks (the non-uniformity factor is of 80% of the mean request inter-arrival period). Left: FR-FF (squares) and FAR-FF with 3 alternate paths (circles); right: AUR-E

Finally, the modified-RANNET topologies were investigated for the static case wavelength requirement. Similar results were obtained as before. A difference in the physical topology of just one link can lead to very different network performance both in terms of the wavelength requirement in static operation and the network forecast tolerance.

In summary, the method of designing a static wavelength-routed optical network, to minimise the number of wavelengths required has been shown to lead to robust dynamic wavelength-routed network designs, for the first time. The results of [Bar96] show that the wavelength requirement in static operation generally reduces with increasing physical connectivity. It is shown here that networks with the same value of physical connectivity but higher static case wavelength requirements generally have lower traffic forecast tolerance. Secondly, it has been shown that even a single

physical link change in the network topology can lead to a large variation in the network traffic forecast tolerance; hence both the initial network deployment and later network expansion should be carefully planned. It is desirable to arrange the physical links in a way that leads to a relatively low static case wavelength requirement, which generally leads to lower blocking probability in uniform traffic and also higher tolerance to future traffic pattern changes. However, some discrepancies have been found where high static case wavelength requirements do not necessarily result in lower traffic forecast tolerance of the network. On average, the static case wavelength requirement can give a good prediction of the network robustness against significant changes of the traffic patterns. Finally, the results strengthen the findings in Section 4.2.2, that the low blocking probability with uniform traffic means higher network tolerance to traffic pattern variations. This can be explained as being due to the lower blocking probability leaving the network more flexibility to handle future unpredictable traffic pattern variations.

#### 4.4 Further Investigation on Randomly Connected Networks of Different Scales

In this section, an investigation of both the average lightpath length and the static case wavelength requirement was carried out on a wide variety of network topologies to further investigate the impact of the physical topology with the performance of dynamic wavelength-routed optical networks.

Randomly connected network topologies, generated with the condition that the minimum nodal degree  $\delta_{min} \geq 2$ , were used in this study. Five network sizes were considered, with numbers of nodes  $N = 14, 21, 28, 35$  and  $42$ . For each value of  $N$ , physical connectivities  $\alpha = \frac{2L}{N(N-1)}$  ranging from 0.05 to 0.7 were considered. This

choice of the range of network sizes and physical connectivities covers most practical core and metro networks. It should be noted that the assumption of the minimum nodal degree  $\delta_{min} \geq 2$ , restrict the physical connectivity range for different sizes of networks. In particular, for networks with  $N=14$ , the

minimum  $\alpha_{min} = \frac{2}{N-1} = \frac{2}{14-1} \approx 0.15$ , whereas for networks with  $N=42$ , the

minimum  $\alpha_{\min} = \frac{2}{N-1} = \frac{2}{42-1} \approx 0.048$ . For each network size  $N$ , 5 values of  $\alpha$  were chosen, which cover the minimum physical connectivity and relatively larger physical connectivity, consistent with most of the current practical networks. Next, for each value of  $\alpha$ , 25 randomly connected network topologies were created and tested. Wavelength conversion facility was not considered in the investigation.

FAR-FF RWA algorithm was employed with 3 shortest disjoint paths for each network node-pair. The networks were first tested with uniform traffic loading, with further calculations of wavelength requirement in static operation, assuming a single bidirectional lightpath per node pair and the average lightpath length. The method used to compute  $N_\lambda$  is given in Appendix B as discussed in Section 4.3.2. In addition, the calculation of the average lightpath length is based on the “K Shortest Path Routing” algorithm proposed in [Epp94], rather than directly collected data from simulation. The formal description of the theoretical calculation process based on “K Shortest Path Routing” is given in Appendix C. The networks were then tested with non-uniform traffic with large traffic pattern variations. However, due to the high computational complexity, a subset of the randomly connected networks of different sizes, chosen on a random basis, were used to investigate traffic forecast tolerance. The standard deviation of blocking probability with non-uniform traffic was compared with the calculated  $N_\lambda$  and the average lightpath length to assess their correlation.

In the case of uniform traffic loading, the lightpath requests were generated with Poisson distributed inter-arrival times, and exponentially distributed holding times with unity mean. In addition, to enable direct comparisons between the performances of different sized networks, the average offered load to each transmitter at each wavelength was scaled to

$$K = \frac{N(N-1) \frac{1}{\mu_u}}{2LW} \quad (4.13)$$

so that the mean lightpath request inter-arrival time was set to

$$\mu_u = \frac{N(N-1)}{2LWK} = \frac{1}{\alpha WK} \quad (4.14)$$



where  $W$  is the number of wavelengths per fibre,  $K$  is the average offered load to each wavelength transmitter,  $\alpha$  is the physical connectivity, and  $L$  is the number of physical link with two fibres (one for each direction). The number of wavelengths per fibre was set to  $W = 16$  in all cases.

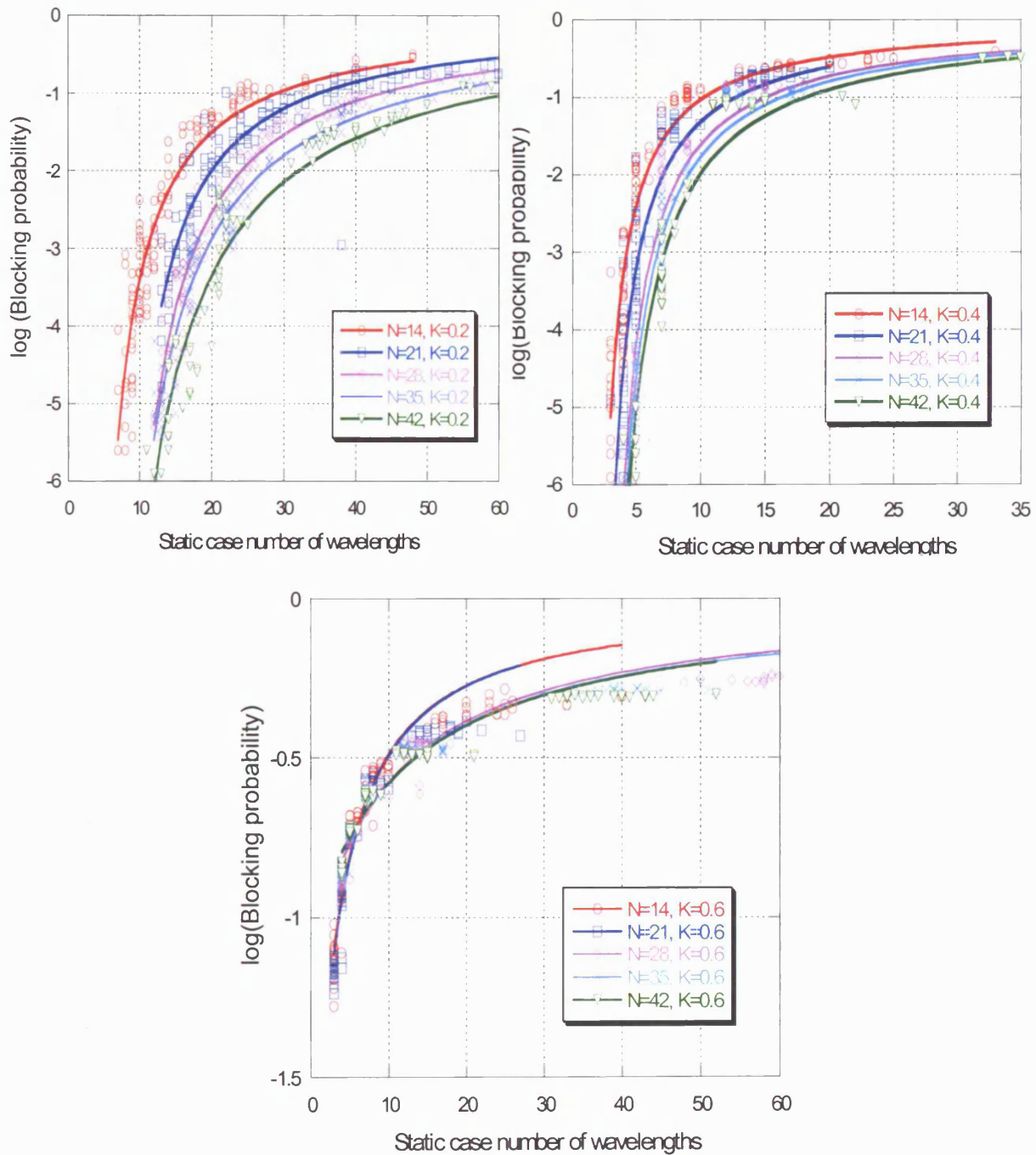


Figure 4.20 - Blocking probability in uniform traffic versus static case wavelength requirement,  $N_\lambda$ , of randomly connected networks with  $N=14, 21, 28, 35, 42$  for top left:  $K=0.2$ ; top right:  $K=0.4$ ; bottom:  $K=0.6$

The results of  $K=0.2, 0.4$ , and  $0.6$  are presented. In the case of non-uniform traffic, the non-uniformity factor was chosen to be 80% of the mean lightpath request inter-arrival time, to assess the effects of a large degree of traffic pattern variations.

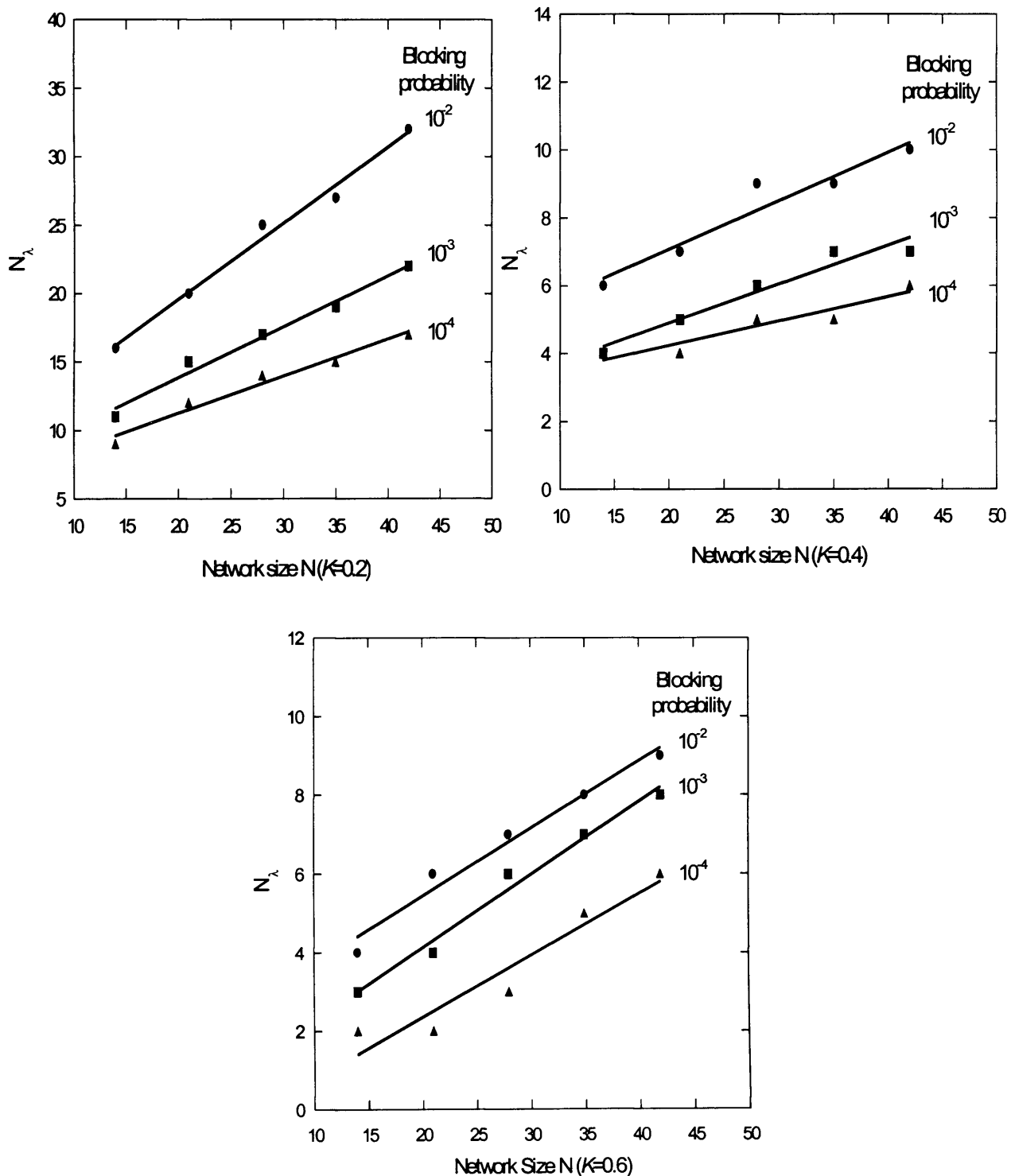


Figure 4.21 - Static case wavelength requirement,  $N_\lambda$ , versus network size with blocking probabilities  $10^{-2}$ ,  $10^{-3}$ ,  $10^{-4}$  for top left:  $K=0.2$ ; top right:  $K=0.4$ ; bottom:  $K=0.6$

The average blocking probability for each randomly connected network was obtained, with uniformly distributed loads. The plot of blocking probability versus the static case wavelength requirement is shown in Fig.4.20 with five network sizes,  $N=14, 21, 28, 35, 42$  for  $K=0.2, 0.4, 0.6$ . For each value of  $K$ , a clear trend in the relationship between the values of  $N_\lambda$  and the blocking probability with uniform traffic can be observed; for each value of  $N$ , the blocking probability value lies close to a line showing increasing blocking probability with  $N_\lambda$ . As the network size is increased, this line shifts to lower values of blocking probability. It can also be seen that, with the increase of offered load to each wavelength transmitter,  $K$ , the blocking probabilities increase, so that when  $K=0.6$ , the lines for different network size begin to merge with each other and the distribution of blocking probability for each network become very close. Fig.4.21 shows static case wavelength requirement versus all five network sizes exhibiting blocking probabilities of  $10^{-2}$ ,  $10^{-3}$ , and  $10^{-4}$  for  $K=0.2, 0.4, 0.6$ . It can be seen that, for networks of the same size, networks with higher wavelength requirements exhibit higher uniform traffic blocking probability. These results suggest that the network blocking probability performance can be predicted by a simple calculation of  $N_\lambda$ .

Besides the static network wavelength requirement, the average lightpath length in terms of number of hops was also calculated for each of the randomly connected networks. For each network node-pair, the overall lengths of the three link-disjoint shortest paths were summed. The overall average lightpath length for the whole network was calculated as the mean of lightpath lengths for all the network node-pairs. The results are shown in Fig.4.22 for  $K=0.2, 0.4$ , and  $0.6$ . It should be noted that, for the same sized networks with the same physical connectivity (i.e. the same value of  $N$  and same value of  $L$ ), different physical topologies gave different value of the overall average lightpath lengths, though their approximate lower bound is the same. The lower bound of the average lightpath length was discussed previously, in Section 4.2.1. Since the average network nodal degree is

$$\delta = \frac{2L}{N} \quad (4.15)$$

according to equation 4.3, the lower bound of average hightpath length is

$$h \approx \frac{\ln \left[ 1 + (n-1) \frac{\delta-2}{\delta} \right]}{\ln(\delta-1)} \approx \frac{\ln \left[ 1 + (N-1) \frac{L-N}{L} \right]}{\ln(\frac{2L-N}{N})} \quad (4.16)$$

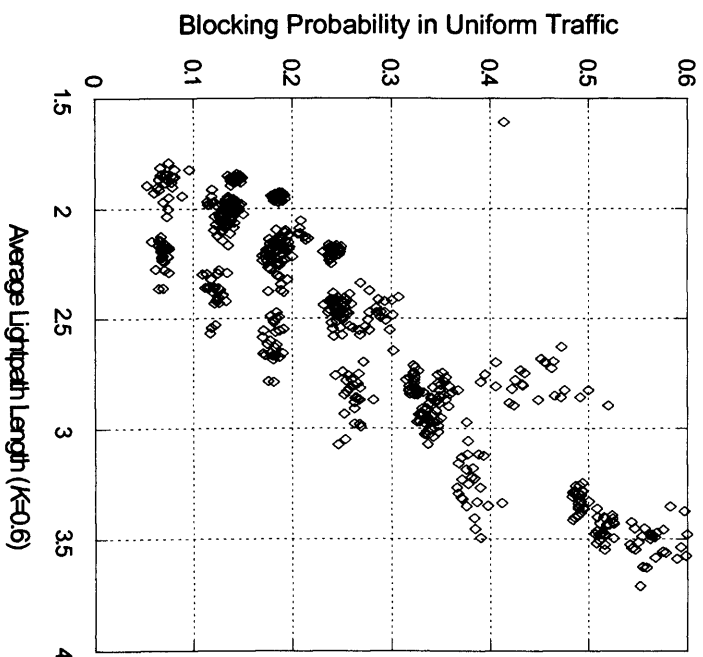
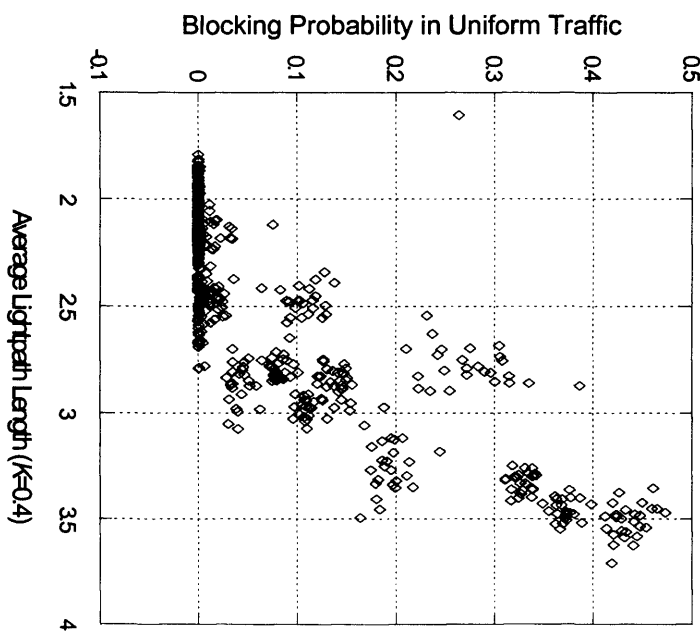
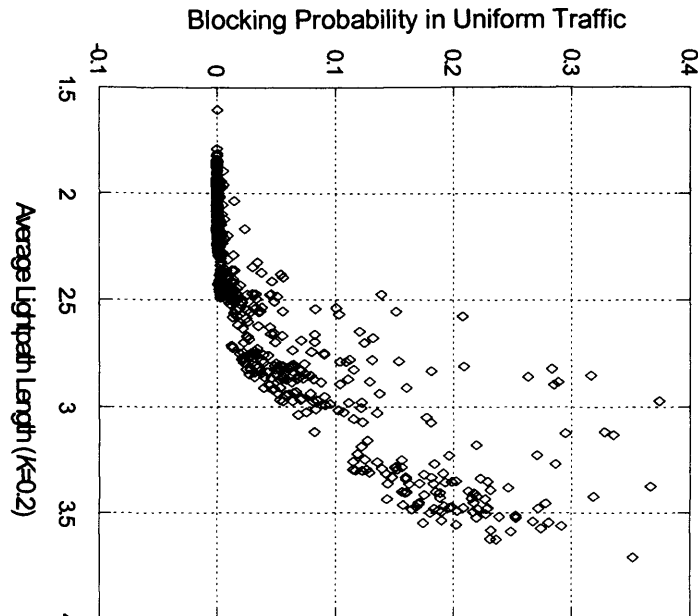


Figure 4.22 - Blocking probability in uniform traffic versus average lightpath length of randomly connected networks with  $N=14, 21, 28, 35, 42$  for top left:  $K=0.2$ ; top right:  $K=0.4$ ; bottom:  $K=0.6$

The results of the average lightpath length and the blocking probability with uniform traffic are shown in Fig.4.22. A clear trend can be observed; for all network sizes, the networks with longer average lightpath lengths show higher uniform traffic blocking probabilities. The phenomenon is consistent for all values of  $K$ . These results suggest that the calculation of the average lightpath length gives a reliable prediction of the network blocking probability performance. In addition, the average lightpath length can be used as a good reference when comparing the performance of networks with the same size and the same number of links.

Besides the blocking performance with uniform traffic, the randomly connected networks were also tested with non-uniform traffic, to investigate the networks' traffic forecast tolerance. Due to limited computing resources, only a subset of the networks was tested, representing the full range of physical connectivity values at each network size. All the chosen networks were tested with large traffic pattern variations. Specifically, the non-uniformity factor was set to 80% of the mean traffic request inter-arrival time, and the standard deviation of the blocking probabilities was calculated. The results are shown in Fig.4.23. A clear relationship can be observed between the average blocking probability with uniform load, and the standard deviation of blocking probability with large traffic pattern variations (Fig.4.23 Left). For each size of network, the values lie close to a line showing increasing blocking probability with uniform traffic and increasing blocking probability standard deviation with non-uniform traffic loading. The results show that larger networks ( $N>21$ ) exhibit higher tolerance to traffic forecast uncertainties. It also shows that, for larger networks, the network tolerance is independent of the network size. In addition, the strong dependence of the blocking probability standard deviation on the uniform traffic blocking, which itself is related to  $N_\lambda$  (as shown in Fig.4.20), implies that a reliable prediction of the network tolerance can be made from the number of wavelengths required to interconnect all network node-pairs in static configuration. A clear relationship can be observed in Fig.4.23 (right). Again, the values for networks with  $N=14$  and 21 and networks with  $N>21$  can be observed, scattered above and

below the curve. The static network wavelength requirement can provide an estimate of the network traffic forecast tolerance, regardless of the network size.

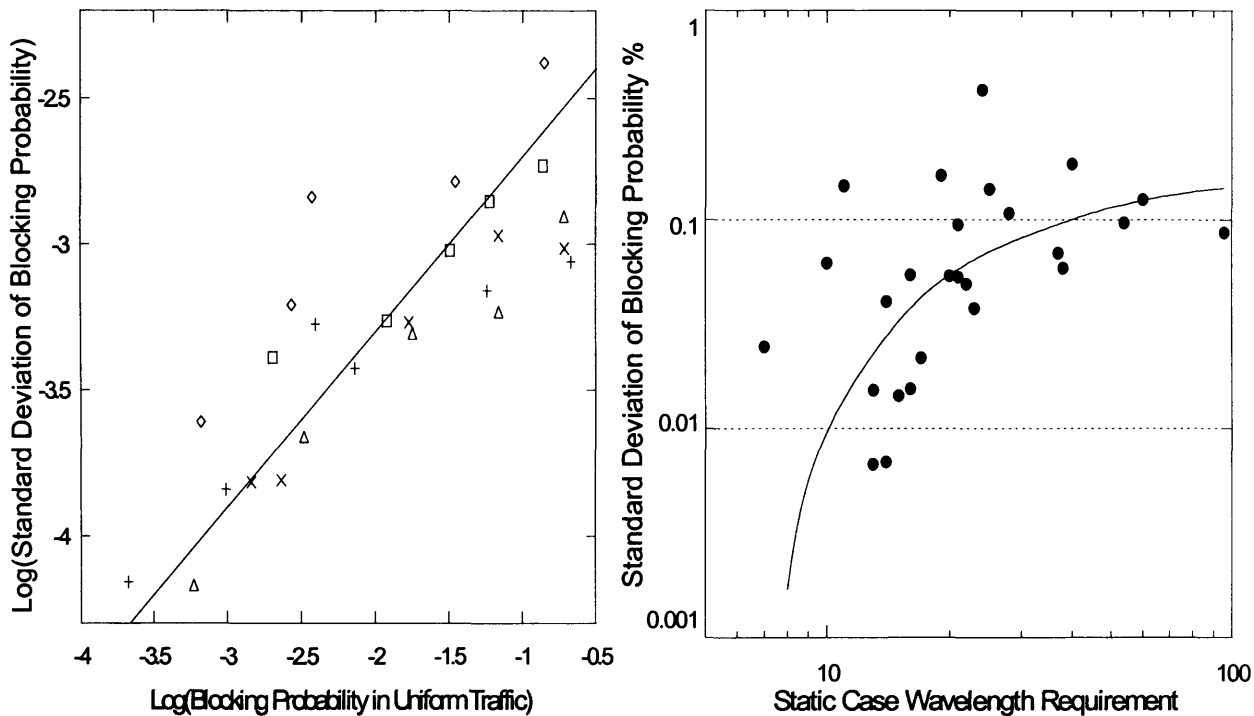


Figure 4.23 - Left: standard deviation of blocking probability with non-uniform traffic versus blocking probability with uniform traffic for network size  $N=14$  (diamonds), 21 (squares), 28 (crosses), 35 (triangles), 42 (pluses). Right: relationship between standard deviation of blocking probability and static case wavelength requirement for tested networks on left.

In summary, an investigation of a large variety of randomly connected networks with a wide range of sizes and physical connectivities was carried out. The results have further strengthened the findings in Section 4.2.2 and Section 4.3.3 for real practical networks. Firstly, the networks with low blocking probabilities with uniform traffic tended to exhibit high network tolerance to traffic pattern variations. Secondly, the blocking probability with uniform traffic increased with average lightpath length, and hence this parameter gives a good indication of the traffic forecast tolerance of the network. Thirdly, the wavelength requirement in static operation,  $N_\lambda$ , also shows an increase with the blocking probability with uniform traffic, hence it also can be used

to make a reliable prediction of the traffic forecast tolerance. Finally, both  $N_\lambda$  and the average lightpath length in the network can be used in a reliable method to predict the network traffic forecast tolerance, reducing the computational effort required in the design of robust dynamic wavelength-routed networks.

## 4.5 Summary

In this chapter, a study has been conducted on the influence of the physical features of a dynamic wavelength-routed optical network topology on its traffic forecast tolerance. In particular, the investigation focused on the average lightpath length in the network, and the wavelength requirement to fully interconnect all the nodes in static operation.

Firstly, a theoretical lower bound on network average lightpath length was derived and discussed. Secondly, it was observed that even a single physical link difference in the network topological layout may lead to significant variation in the average lightpath length, and hence a large change of the network performance. In addition, a strong correlation was observed between average lightpath length and traffic forecast tolerance. However, it should be noted that this phenomenon is particularly obvious when the RWA algorithm considers more alternate paths for each node-pair, since, with this type of RWA scheme, the blocking performance mainly depends on the average distance of the lightpaths. With the wavelength continuity constraint, the further a lightpath has to travel, the more difficult it is to find an available wavelength to establish the lightpath. Hence, any small physical link changes that decrease the average lightpath lengths will lead to a significant overall lower blocking probability. Moreover, the improved blocking performance gives the network more flexibility to tolerate future traffic pattern variations, in other words, increases the traffic forecast tolerance of the network. Thirdly, it has also been observed that a single physical link difference may lead to significant variation in the wavelength requirement in static operation. It was shown that networks with lower wavelength requirements exhibit a higher traffic forecast tolerance. Finally, it can be concluded that networks with lower blocking probability performance with uniform traffic generally tend to show higher traffic forecast tolerance. Since the calculation of the average lightpath length and the

wavelength requirement to fully interconnect the nodes in static operation can give a reliable prediction of the network traffic forecast tolerance, extensive computer simulations can be avoided in designing dynamic wavelength-routed networks.



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## Chapter 5 Investigation of Wavelength Conversion on Traffic Forecast Tolerance

### 5.1 Introduction

As discussed in Chapter 2, wavelength conversion, the function of switching the optical signal from one wavelength to another, is commonly used in wavelength-routed optical networks. Wavelength conversion is normally performed at the OXCs in the network nodes. The introduction of the wavelength conversion facility removes the wavelength continuity constraint, so that a lightpath does not necessarily travel on the same wavelength along all the physical links of the path between the source and destination nodes, increasing the probability of a lightpath being successfully established. Wavelength conversion can significantly improve the blocking performance for dynamic wavelength-routed optical networks. In addition, the fairness for the longer lightpath connections is improved. Many studies have been carried out to assess the benefits of wavelength conversion [Bar96][Kov96][Sub96][Bir96][Lu03][Zhu00][Sub97][Kar98][Har98][Tri00][Sha00][Ram02]. However, there are few studies focused on dynamic wavelength-routed optical networks with wavelength conversion under large traffic pattern variability. Consequently, it is important to evaluate the advantage of wavelength conversion in improving network traffic forecast tolerance.

In this section, various wavelength conversion schemes are introduced first. A variety of routing and wavelength allocation algorithms with wavelength conversion and optimal wavelength conversion placement schemes are discussed. Following this, network traffic forecast tolerance is assessed in the presence of wavelength conversion for various networks. Finally, a comparison is given of two sparse wavelength conversion schemes under large traffic pattern variability.

### 5.1.1 Wavelength Conversion Scheme

The wavelength conversion function is realized by a device, referred to as a wavelength converter. A wavelength converter can switch an incoming wavelength  $\lambda_i$  to an outgoing wavelength  $\lambda_j$ . It would be ideal to equip the dynamic wavelength-routed optical network with 'full' wavelength conversion facility so that each network node can switch any incoming wavelength to any outgoing wavelength. The wavelength converters that are used to realise the 'full' wavelength conversion are referred to as full-range wavelength converters. In this case, the dynamic wavelength-routed optical network can be regarded as operating like a traditional circuit-switched telephony network, where the wavelength continuity constraint does not exist. An example of an optical cross-connect with full wavelength conversion architecture is discussed and shown in Fig.2.8. However, since wavelength converters are likely to remain costly devices in the foreseeable future, it is not practical to install 'full' wavelength conversion in every node in the network. The need to keep costs low in the network is the reason that sparse wavelength conversion schemes have been proposed. There are three main sparse wavelength conversion schemes, referred to as limited-range wavelength conversion, sparse nodal conversion, and sparse switch-output conversion.

In contrast to full-range wavelength conversion, with limited-range wavelength conversion, the monetary and power costs are reduced by limiting the conversion range of the wavelength converters. In particular, it is more efficient for some wavelength converter design technologies (wave-mixing-based technologies) to convert to wavelengths that are closer than to those that are further away. For other wavelength converting approaches, especially optoelectronic converters as discussed in Section 2.2.3.5, it is cheaper to have a limited number of output wavelengths that can be converted to.

In sparse nodal conversion, the design aims to reduce the costs by allowing only a few network nodes to have full-range wavelength conversion capabilities. However, the placement of network nodes with full-range wavelength conversion is a critical issue, as different placement decisions might lead to variations in network performance.

In sparse switch-output conversion, the design attempts to reduce the costs by limiting the number of wavelength converters at each network node. It has been observed that a node equipped with full wavelength conversion does not tend to utilise all the wavelength converters [Ine99]. There are two reasons for this phenomenon. Firstly, only traffic passing through the network node may use the wavelength converters, whereas traffic originating from or destined for the network node will not use the wavelength converters. It is easy to understand that if the amount of bypassing traffic is low, a few wavelength converters will be sufficient. Secondly, in wavelength-routed optical networks, lightpaths are usually routed using fixed physical paths in a way that minimises the use of wavelength converters.

It has been pointed out clearly that partial/sparse wavelength conversion can achieve nearly the same performance as that of full wavelength conversion [Sub96][Lu03][Ram02]. Many studies have focused on the benefit of full-range wavelength converters which can switch any input wavelength to any output wavelength [Bar96][Kov96][Bir96][Sub97][Kar98][Ram02]. However, full-range wavelength converters come with technological difficulty or high cost to implement. As a result, limited-range wavelength converters become of interest. It has been shown that limited-range wavelength converters can achieve the same blocking performance as full-range wavelength converters in [Yat96][Har98][Tri00][Sha00]. Moreover, with sparse nodal conversion, studies show that, through careful selection of network nodes with full-range wavelength conversion capability, it is possible to achieve the same benefits as equipping all network nodes with full conversion capabilities [Ine99].

### 5.1.2 Optimal Wavelength Conversion Placement

With sparse wavelength conversion schemes, optimal wavelength conversion placement naturally becomes an important issue. It is necessary to deploy the sparse wavelength conversion facility in the wavelength-routed network in a way that leads to optimal network performance while saving expensive wavelength conversion resources.

A general solution to solve the wavelength conversion placement problem usually follows two steps. The first step is to calculate the minimum blocking probability using full wavelength conversion at every network node. The second step is to assign wavelength conversion to certain set of network nodes under certain constraints, either exhaustively or partially, and compare the blocking probability against the optimal performance in the first step. These studies include [Jeo05][Xia99][Li02][Gao03][Cao05][Ven99][Thi99][Aro00][Wan01][Din03][Sub99]. A recent study for the placement of limited-range wavelength converters has been performed based on a binary linear program (BLP) formulation, in which the network-wide blocking probability is expressed as a linear function of converter locations so that the standard linear program optimization can be employed to obtain the optimal solution [Jeo05]. It is claimed that, based on this proposed binary linear program formulation, the optimal placement solutions can be obtained for moderate and large networks with a reasonable amount of computation time. It is argued that previous studies of the wavelength converter problem using BLP formulation [Xia99][Li02][Gao03] do not necessarily minimize the network-wide blocking probability. In [Cao05], the optimal placement of wavelength converters was considered together with the placement of optical splitters for multicast in WDM networks. An integer linear programming (ILP) model was proposed to solve the optimisation problem while minimising the total number of wavelength channels required. It was shown that the splitter placement and wavelength converter placement tend to have a close relationship. In [Ven99], a heuristic algorithm was proposed for placing limited range wavelength converters while keeping low blocking probabilities. The basic principles behind the algorithm are to equip with wavelength conversion the most congested network nodes, nodes which lie on the long lightpaths, and nodes where conversion of the optical signals is significantly high. In particular, wavelength converters should be placed at the nodes which have a high nodal degree, transit large amounts of traffic, convert a large number of optical signals, and nodes which are adjacent to the nodes with large transit traffic. An analytical model has been derived for the placement of wavelength converters in a ring network topology, whereby the wavelength converters are placed as uniformly as possible in the ring. In [Thi99], the authors proposed an algorithm which develops the traditional method of exhaustive placement and blocking performance computation by calculating the blocking performance of only some converter placement combination. It was shown

that the new algorithm can reduce the high computational requirements of the original method. In [Aro00], another algorithm was proposed for the wavelength converter problem aiming to minimize the blocking probability of an arbitrary route. The algorithm equips the network nodes that have the highest outgoing traffic with wavelength conversion. It is shown that optimal network performance can be obtained. A similar idea was employed in [Wan01] in that using wavelength conversion in only some of the “key” network nodes can achieve optimal performance. In [Din03], a blocking island hierarchy (BIH) was constructed based on blocking islands (BI) to calculate the bottleneck causing the blocking probability, which was further utilised to identify the network nodes that need to be equipped with wavelength conversion. A heuristic algorithm aiming to minimize the path blocking probability was proposed in [Sub99] in order to achieve a relatively low network-wide blocking performance. However, it is only applicable on bus and ring network topologies.

Some further studies were carried out on the wavelength converter placement (WCP) problem in a complex environment and the problem studied from different perspectives. In [Tam04a], a study was carried out on the wavelength converter placement with non-uniform traffic. The solution extends the normalized cut based graph partitioning technique, which was proposed in [Tam04b] by the same authors. It was shown that the normalized cut technique can be used to identify network nodes for converter placement with better efficiency and lower complexity. In addition, another study carried out in [Hou03] also considered the converter placement problem under non-uniform traffic loading. The study made the first attempt to solve the wavelength converter problem using the k-Weighted Minimum Dominating Set (k-WMDS) approach and compared it against the approach referred to as k-BLK, which was independently proposed in [Ine99]. It was shown that k-WMDS outperforms k-BLK in terms of the number of converters. In [Jia02], the WCP problem was solved in order to minimize the total wavelength usage in WDM networks. The algorithm proposed can help achieve an understanding of the relationship between the number of wavelengths required and the placement of wavelength converters.

Besides the general proposed solutions for the WCP problem, other studies have been carried out to challenge the traditional methodologies for solving this problem. In [Run04], a generic algorithm is proposed to solve the wavelength converter placement

problem. It is argued that the number of wavelength converters should not be considered as a given parameter, as the number may not be known at the network design process. It is more appropriate to take the converter placement problem as a design variable. In [Chu03a], a study is presented showing that the wavelength converter placement and the RWA algorithms are closely related, in the sense that a well-designed converter placement mechanism for one particular RWA algorithm might not work well with a different RWA algorithm. Moreover, the authors proposed two heuristic algorithms for the converter placement problem, one is termed minimum blocking probability first, the other is termed weighted maximum segment length, under fixed-alternate routing (FAR) and least-loaded routing (LLR) respectively.

### 5.1.3 RWA Algorithms with Wavelength Conversion Facility

In the previous chapters, the studies focused on dynamic wavelength-routed optical networks with wavelength continuity constraint throughout. The RWA algorithms discussed and employed in the study did not take wavelength conversion into consideration. However, when wavelength conversion facility is introduced in dynamic wavelength-routed optical networks, it is necessary to adapt the RWA algorithm and utilise the wavelength conversion while minimizing the blocking probability and saving resources for future traffic. Many previous studies have been carried out taking wavelength conversion into account.

Many studies have been performed in assessing the routing and wavelength allocation algorithm employing wavelength conversion. These generally fall into two main categories, the static RWA algorithm and the dynamic RWA algorithm, often referred to as off-line and on-line RWA algorithm. In the static RWA case, all the lightpath/connection requests for node-pairs are known in advance, thus an RWA algorithm is used to accommodate all the connection requests while minimizing the network resources. The static RWA algorithm is briefly discussed in Section 4.3.1 and Section 4.3.2. In recent years, many studies have been carried out in this area [Cav02][Cav04a][Qin02][Fuq03][Fuq04][Zha03]. However, dynamic RWA algorithms with wavelength conversion are of more relevance to this work. In such cases, the lightpath/connection requests arrive at the network dynamically and are not



known in advance. Thus, the aim of the dynamic RWA algorithm is to minimize the blocking probability while maximising the saving of network resources for use by future traffic. Dynamic RWA algorithms without wavelength conversion are discussed in Section 3.2.3.

In [Chu03b], a dynamic RWA algorithm was proposed, termed weighted least-congestion routing and first-fit wavelength assignment (WLCR-FF) RWA algorithm. The algorithm considers both the distribution of free wavelengths and the length of each route jointly. In addition, it is argued that an effective RWA algorithm needs to take into account the presence of wavelength conversion jointly whereas some of the existing dynamic RWA algorithms largely fail in the presence of wavelength conversion. The same authors further extended the investigation of the dynamic RWA algorithm in conjunction with wavelength conversion in [Chu05]. In [Le05], a novel dynamic RWA algorithm was proposed, based on the combination of a mobile agent technique and a genetic algorithm. The introduction of mobile agents in the network allows the fast synchronization of the network state information and continuous update of the routing tables. The results demonstrate that the proposed algorithm has the capabilities of achieving a better load balance and a significantly lower blocking probability than that of the FAR algorithm for both sparse, full-range wavelength conversion and sparse, limited-range wavelength conversion. In [Cav04b], two dynamic RWA algorithms are proposed to solve the routing and wavelength assignment jointly, aiming to minimize the number of wavelength converters used and the number of wavelengths used respectively. The results provide strong evidence that the algorithm which minimizes the number of wavelength converters performs better than the one which minimizes the number of wavelengths used, in terms of blocking probability, number of path hops, and the network cost. In [Zha02], a dynamic RWA algorithm is proposed based on the weights of the links. The weight is a function of the availability of each wavelength on the input and output links of a node and the number of available wavelength converters. In addition, the cost of wavelength conversion is taken into consideration, so that the selected wavelengths yield the lowest conversion cost. Results show that the algorithm is particularly effective when the number of wavelengths is large while the number of wavelength converters is limited.

In addition to the direct studies for dynamic RWA algorithms with wavelength conversion, further studies focused on different aspects of the RWA algorithms with wavelength conversion. In [Li03], the authors present arguments that the RWA has to take into consideration the wavelength converter placement process, and thus calls for re-examination of both RWA and wavelength converter placement. The argument is verified by two studies. Firstly, it is shown that the proposed WLCR-FF algorithm [Chu03b] outperforms all existing RWA algorithms (static, fixed-alternate, and least-loaded routing) in sparse or full wavelength conversion environments. Secondly, results show that the proposed weighted maximum segment length (WMSL) algorithm for a dynamic RWA algorithm can outperform, by a large margin, all existing wavelength converter placement algorithms in terms of blocking probability. In [Zho02], the authors investigated the impact of imprecise network state information on the performance of dynamic RWA algorithms with wavelength conversion. It is argued that the non-negligible propagation delay, infrequent state updates due to overhead concerns, and hierarchical topology aggregation, can affect the precision of the global network state information. Many dynamic RWA algorithms were tested with partial network state information, showing that new RWA algorithms that can tolerate imprecise global network state information may need to be developed for dynamic connection management in future WDM networks. In [Man03], a study was carried out focusing on the dynamic wavelength selection algorithm for optical networks with limited wavelength conversion capability. It was claimed that the proposed wavelength selection algorithm can work efficiently for a reasonable size of networks, and may help to improve the network resource utilization with existing dynamic routing strategies. In [Zha02], a test was performed on the effects of different dynamic RWA algorithms on limited-range wavelength conversion in terms of blocking performance gain. In particular, a comparison was made on the FR-FF and FAR-FF algorithms using semiconductor optical amplifier (SOA) and four wave mixing (FWM)/cross-gain modulation (XGM) technologies based wavelength converters, which are discussed in Section 2.2.3.5. It was found that the performance gain of the XGM based wavelength converter was not as great as that of FWM based wavelength converter. In alternate routing RWA algorithms, increasing the number of alternate paths, leads to a reduction in the range of the FWM wavelength converters required to approach the performance of the network with ideal full-range wavelength converters.

Further studies were carried out on the operation of dynamic wavelength-routed optical networks with wavelength conversion capabilities, in which a scheme was developed to dynamically assign conversion resources to traffic requests on demand, referred to as dynamic conversion resources allocation algorithm (CRAA) in [Hab04]. In [Hab04], the authors aim to optimize the allocation of scarce wavelength conversion resources using different CRAA algorithm scenarios that change the behaviour of the traffic blocking models in the share-per-link wavelength converting switches. In particular, the narrow search algorithm (NSA), inclusive search algorithm (ISA), and optimized inclusive search algorithm (OISA) were studied. It was found that ISA is characterised by a high computational complexity and requires higher processing load to achieve better allocation rate than NSA, whereas the OISA minimizes the exhaustive nature of the ISA search and results in a comparable performance. In [She00], a simple iterative heuristic algorithm was proposed to operate the networks with wavelength conversion facility with the FR-FF algorithm, which is proved to be efficient and fast. In [Bos02], besides the proposed path-metric dynamic RWA algorithm as discussed above, the authors also developed a dynamic scheme to adopt the path-metric algorithm. The principle behind the operation scheme is to choose the highest value path for node-pairs to establish lightpaths considering path length, wavelength usage, and converter locations.

In this chapter, the results of optimal wavelength conversion placement are employed in assessing network traffic forecast tolerance. In addition, a new operating scheme is proposed, based on the previously studied scheme described in [She00]. Details are discussed in Section 5.2. Moreover, a variety of wavelength conversion schemes are compared in terms of network traffic forecast tolerance.

## 5.2 Wavelength Conversion on Traffic Forecast Tolerance

As discussed in Section 5.1, the introduction of wavelength conversion to the dynamic wavelength-routed optical network breaks the wavelength continuity constraint and hence improves the network performance. In the context of traffic forecast tolerance, it is important to evaluate the advantages of wavelength conversion that might enhance the robustness of the network to unpredictable traffic pattern variations.

However, to the best of the author's knowledge, there are few studies regarding this topic in the literature.

### 5.2.1 Novel dynamic operating scheme

A novel algorithm is introduced to apply the FAR-FF algorithm to the dynamic wavelength-routed optical network. The algorithm extends the proposal in [She00] which is only suitable for simple routing algorithms, and maximises the gain of the wavelength conversion (defined in [Ine99] as the ratio between the blocking probability difference and blocking probability in the absence of wavelength conversion). The aim of this scheme is to utilize the remaining wavelengths and wavelength converter resources in a conservative way during the dynamic process of servicing connection requests in order to save resources and enhance the probability of successful connection of future lightpath requests. The FAR-FF algorithm considers link-disjoint alternate paths for each node-pair in the network. Consider a new lightpath request between source node  $s$  and destination node  $d$ . There exists a path set (usually the shortest path set) between the node-pair for any given network topology. For any path in the path set between the node-pair, there are  $m$  intermediate nodes (labelled 1 to  $m$  in sequence) and  $m+1$  links ( $m \geq 0$ ). The lightpath for this request can be established if wavelengths and converters for its use may be provided along this path, otherwise the lightpath request is blocked. The details of the algorithm are described below:

#### Phase I: calculation of path set

1. Calculate a link-disjoint path set between node  $s$  and node  $d$  based on Dijkstra's algorithm (the number of paths is set in advance)
2. Label the paths in ascending order in terms of path length with shortest path indexed 1 (random index for same-length shortest paths).
3. Go to Phase II.

#### Phase II: operation of RWA without WC

1. Check if there is any path that has not already been considered (start with the path of the smallest index first). If any such path exists, go to step 2, otherwise go to Phase III.

2. Check if any common wavelength is available on all the links of the path. If any such wavelength exists, assign one with the smallest index to the lightpath and terminate the operation with a success; otherwise go back to step 1.

### **Phase III: operation of RWA with WC**

1. Check if there is any path that has not already been considered (start with the same path set as in Phase I and II with the smallest index path first). If any such path exists, go to step 2, otherwise terminate the operation with a failure.
2. Find the first node  $x$  on the path with free converters available for use. If there is no such node with free wavelength converters, then go to step 1; otherwise continue.
3. Find a common wavelength which is available on all the links up to the node  $x$ . If no such wavelength exists, then go to step 1; otherwise, assign a common wavelength to all the links up to node  $x$  and continue (if there are more than one common wavelength, assign the one with smallest index).
4. Regard node  $x$  as the new source node  $s$  and start again from Phase I.

This iterative heuristic algorithm continues until either the process terminates with a failure, in which case the corresponding lightpath request is blocked, or it succeeds with a choice of converters and wavelengths as indicated by the algorithm itself. The aim of the algorithm is to leave the use of wavelength conversion resources until they really needed. In particular, the algorithm always tries to find a possible connection without using wavelength conversion, until the search for a path without WC is exhausted. It can be seen from the algorithm itself that provided there exists nodes with free wavelength converter along any path between the source and destination nodes, the probability of the successful establishment of a lightpath for the node-pair is highly increased, since every time a node with free wavelength converter is found, the connection distance between the new source node and the destination node is shortened. In addition, as the node with wavelength converters becomes the new source node, more alternate paths between the new source node and the destination node can be found instead of the previous paths in the previous path set. However, the trade-off for lower blocking probability is the higher computational complexity since for each node-pair, the calculation of the path set may be performed more than once. It should be noted that the algorithm can be adapted to a simpler version so that every

time a new “source” node is found, the path considered between the new source node and the destination node remains the same as the original path, which is only a segment of the original path from the previously calculated path set. Thus for any lighpath request, the steps in Phase I need only be carried out once.

### 5.2.2 Effect of WC on TFT

Wavelength conversion was introduced in the practical network topologies. In particular, the NSFNET and UKNET, and the corresponding modified networks. The network topologies are based on those shown in Fig.3.17. The sparse nodal conversion scheme (as discussed in Section 5.1.1) was employed to allow a few of the network nodes to have full wavelength conversion facility. The network nodes with full wavelength conversion were able to switch optical signals from any incoming wavelength to any outgoing wavelength. A simple principle for the optimal placement for network nodes is followed according to the proposed algorithm in [Ven99], so that the network nodes with high nodal degree are chosen first. The network topologies with full wavelength conversion nodes are shown in Fig.5.1. In order to compare the traffic forecast tolerance of different network topologies with previous results without wavelength conversion, the placement of wavelength conversion nodes were kept the same for the different modified-network topologies. It should be noted that this rule has some conflict with the optimal placement algorithm, as some of the nodes with full wavelength conversion might not be those with the highest nodal degree in some of the modified networks. The modified-NSFNET and modified-UKNET topologies were tested with a total offered load of 140 Erlangs and 233 Erlangs respectively, the same values as used in the tests without wavelength conversion described in previous chapters. The NSFNET and modified networks were equipped with 16 wavelengths per fibre, whereas the UKNET and modified networks were equipped with 20 wavelengths per fibre. In the case of wavelength conversion, both sets of networks employed the dynamic operation scheme proposed in Section 5.2.1, based on FAR-FF algorithm considering two shortest alternate paths for each node-pair in order to carry out comparison with the results in the absence of wavelength conversion described previously. As before, the lighpath requests were generated with Poisson distributed arrivals and exponential lighpath holding time with mean unity. To simulate the dynamic traffic pattern variations, the range of non-uniformity factors was chosen to

be between 10% and 40% of the request inter-arrival period for both network types. For each non-uniformity factor, 25 traffic patterns were randomly generated. Results are shown in Fig.5.2 and Fig.5.3.

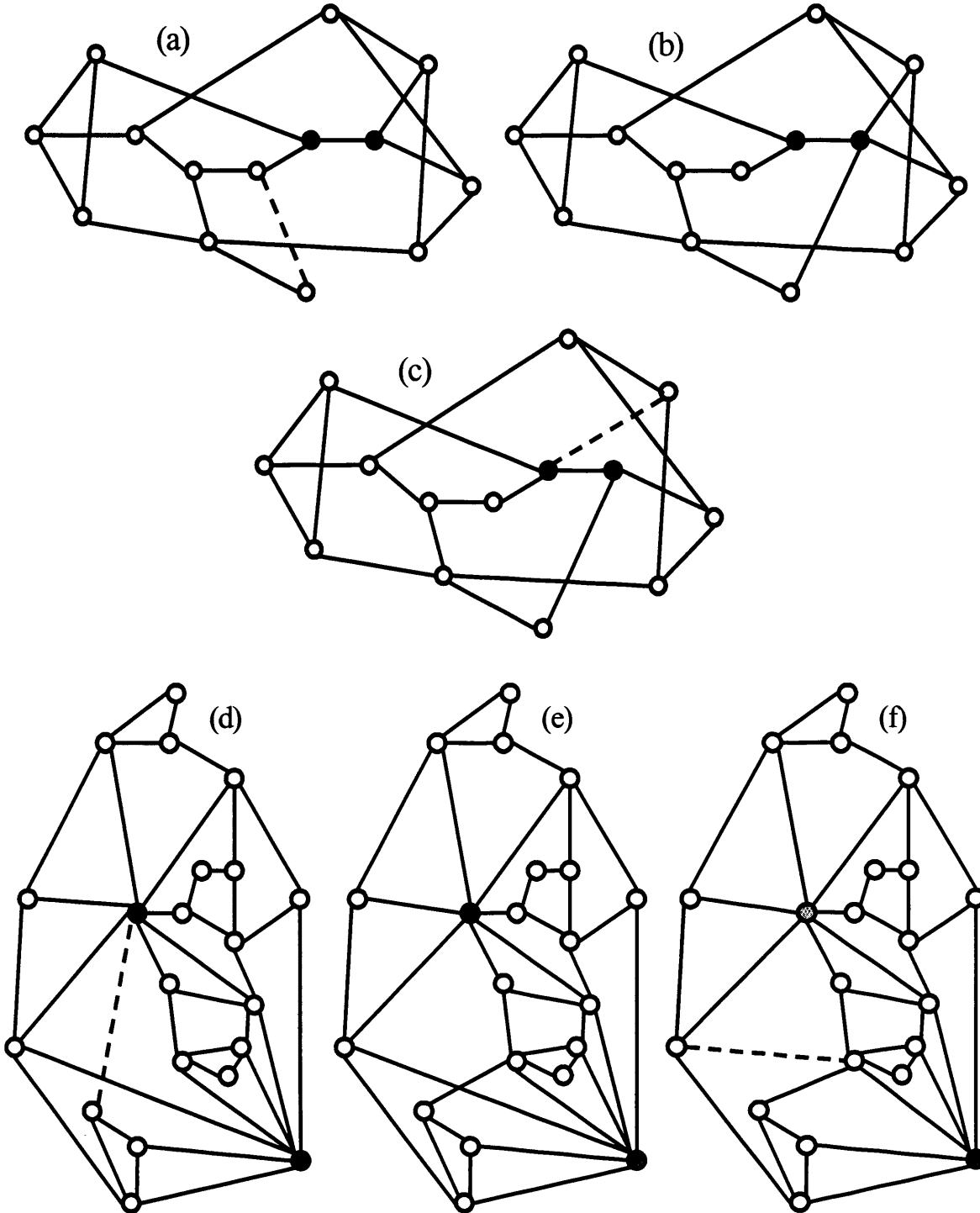


Figure 5.1 - NSFNET (b) and 2 one-link-difference network topologies (a) & (c) of 14 nodes and 21 links (upper); UKNET (e) and 2 one-link-difference network topologies (d) & (f) of 21 nodes and 39 links (down); the nodes in grey are the ones with full wavelength conversion facility.

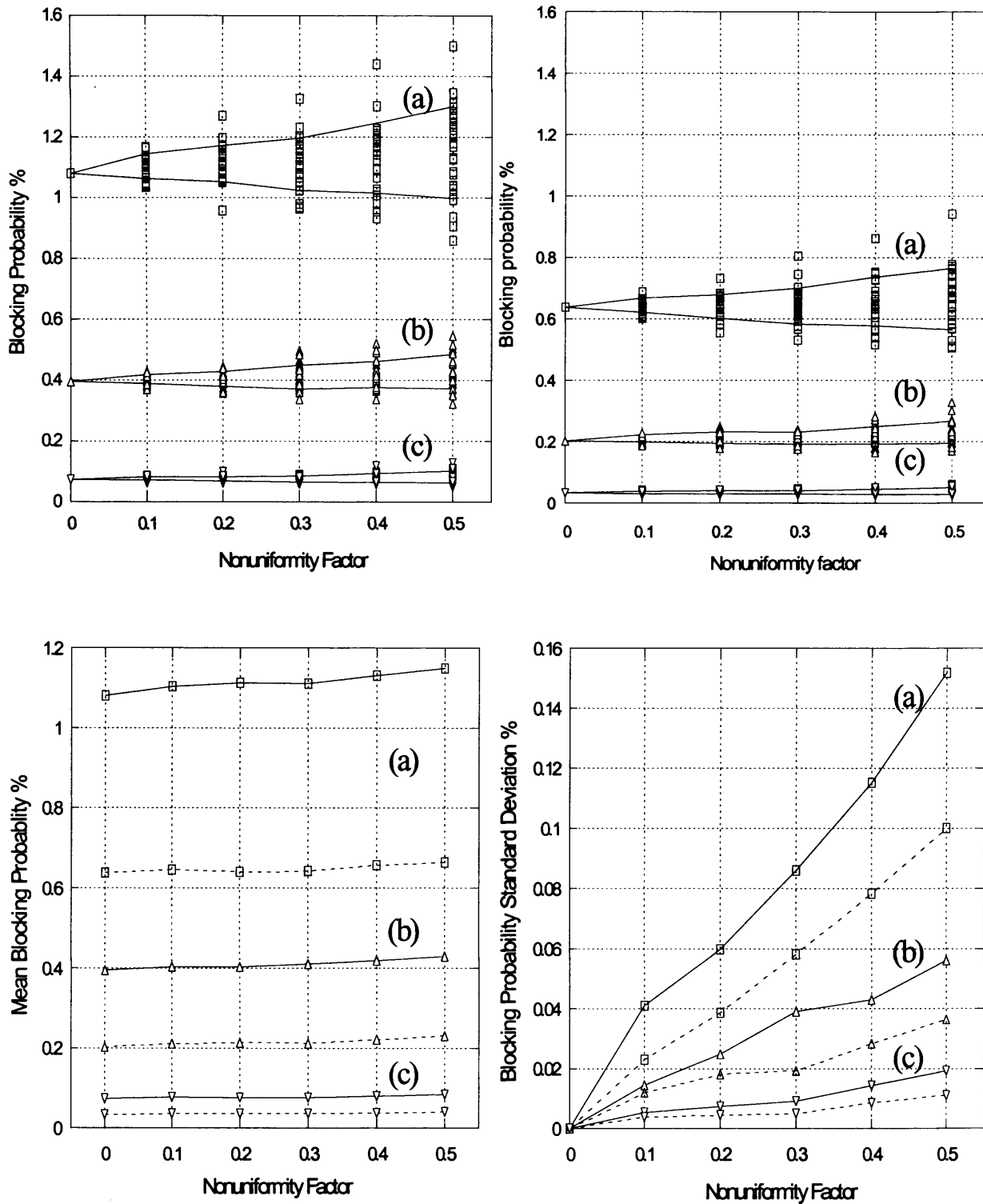


Figure 5.2 - NSFNET (b) and 2 one-link-different network topologies (a) & (c) with (dotted line) / without (solid line) wavelength conversion; upper left: blocking probability versus non-uniformity (without WC); upper right: blocking probability versus non-uniformity (with WC); lower left: mean blocking probability versus non-uniformity; lower right: standard deviation of blocking probability versus non-uniformity



Results of NSFNET and modified network topologies with one-link-difference are shown in Fig.5.2. It can be clearly seen that wavelength conversion enabled a large decrease in the network blocking probability for all three tested networks. In particular, in the plot of non-uniformity versus mean blocking probability, the networks equipped with wavelength conversion showed significant decrease in the blocking performance compared with the same networks in the absence of wavelength conversion. This result is consistent with the findings in the literature discussed in Section 5.1. In addition, it should be noted that networks with higher blocking performance without wavelength conversion showed the largest decrease in blocking when equipped with wavelength conversion, whereas with the networks with relatively low blocking probability without wavelength conversion, the benefit of wavelength conversion was not so apparent. Moreover, with wavelength conversion, the width of the distributions for blocking probabilities for different degrees of traffic non-uniformity is narrower than those of networks without wavelength conversion. This phenomenon is further quantified and clarified in the plot of standard deviation of blocking probabilities versus non-uniformity factor. For all three tested networks, wavelength conversion reduced the standard deviation of the blocking probability for all values of traffic load non-uniformity. The networks with wavelength conversion consequently exhibited higher traffic forecast tolerance. In addition to the increased traffic forecast tolerance, it can be seen that networks with lower robustness to traffic pattern variability in the absence of wavelength conversion have a higher increase in the capability to accommodate the variability when equipped with wavelength conversion. Linking the results of mean blocking probability and standard deviation of blocking probability versus the traffic non-uniformity factor, networks with lower mean blocking probability have higher tolerance to future traffic pattern variations, regardless of whether wavelength conversion is used.

The results of UKNET and modified networks are shown in Fig.5.3. Similar results were found as for the modified-NSFNET networks. Wavelength conversion was found to significantly improve the blocking probability for all three networks tested.

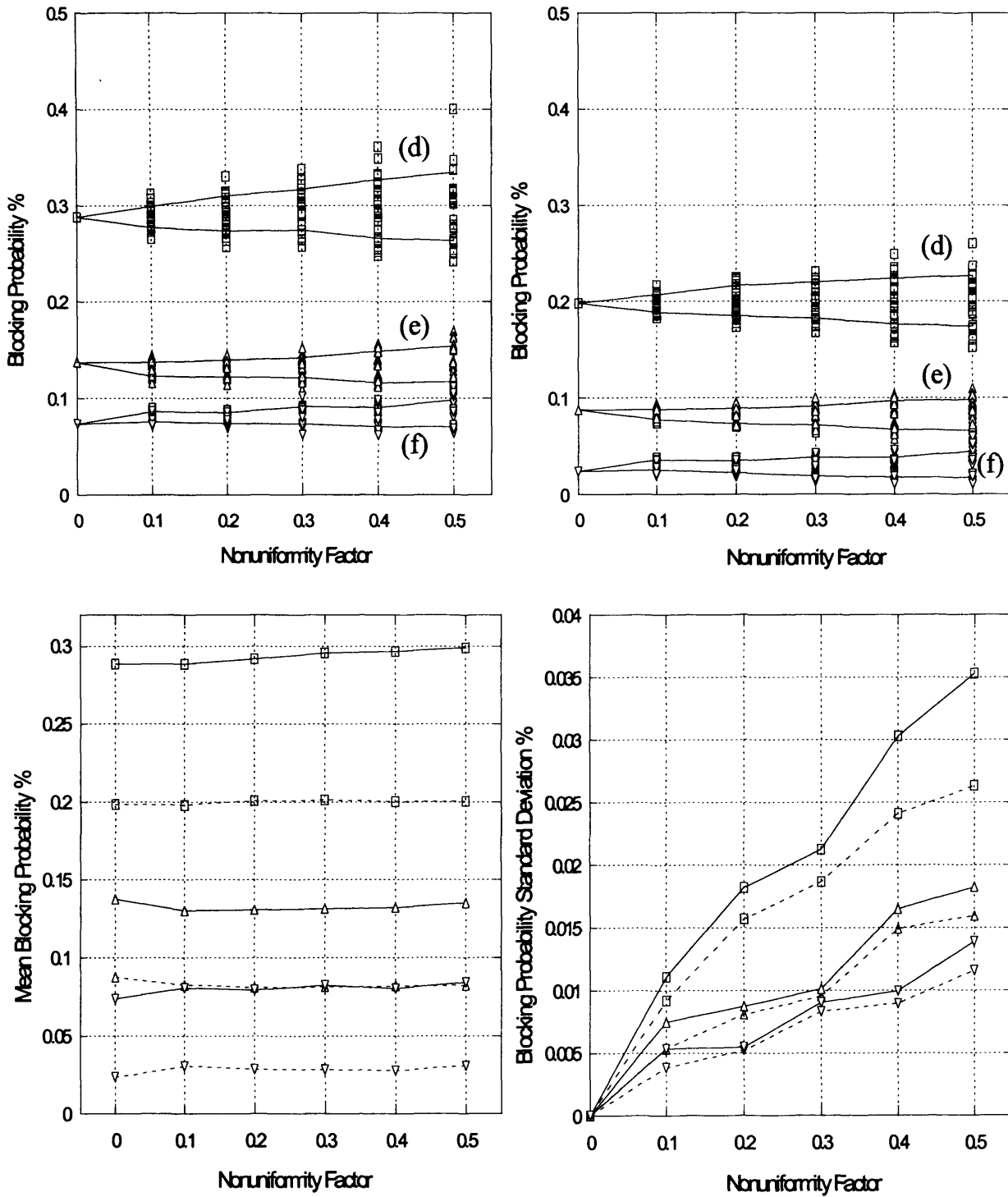


Figure 5.3 - UKNET (e) and 2 one-link-different network topologies (d) & (f) with (dotted line) / without (solid line) wavelength conversion; upper left: blocking probability versus non-uniformity (without WC); upper right: blocking probability versus non-uniformity (with WC); lower left: mean blocking probability versus non-uniformity; lower right: standard deviation of blocking probability versus non-uniformity

In comparison with networks without wavelength conversion, the mean blocking probability is significantly decreased. In addition, the network with higher mean blocking probability without wavelength conversion showed larger decrease in mean blocking probability in the case of wavelength conversion than that of the ones with lower mean blocking probability in the absence of wavelength conversion. Again, when tested under different degree of traffic pattern fluctuations, the networks with wavelength conversion outperform the networks without wavelength conversion. In particular, the width of the distribution for the blocking probability is narrower in the case of wavelength conversion, i.e. the wavelength conversion has improved the network traffic forecast tolerance. In the plot of non-uniformity factor versus the standard deviation of blocking probability, similar findings can be observed as those for NSFNET and related networks. It is shown that networks in the absence of wavelength conversion, with lower traffic forecast tolerance tend to experience higher benefits of wavelength conversion and show larger increase of traffic forecast tolerance with the introduction of wavelength conversion.

In general, wavelength conversion improved the blocking probability of networks and increased the traffic forecast tolerance in the cases of random traffic pattern variations. In addition, the result for both categories of network strengthened the findings discussed in Section 4.5. It is believed that the networks with lower mean blocking performance have more flexibility in dealing with the unexpected traffic pattern fluctuation. This is the case for networks either with or without wavelength conversion.

### 5.2.3 Comparison of Sparse Wavelength Conversion Schemes

In this section, the proposed dynamic traffic model is further employed to investigate two different sparse wavelength conversion schemes, as discussed in Section 5.1.1. The assessment of the effect of different sparse wavelength conversion schemes on network traffic forecast tolerance is further carried out and compared.

Previous studies in the literature focused on the optimal wavelength conversion placement and dynamic RWA algorithm in the case of wavelength conversion. However, an important parameter, the traffic statistics, has rarely been considered in

previous studies. In [Yoo96], it has been stated that the benefit of wavelength converters increases with increasing traffic load, whereas in [Ine99], further investigation was carried out on the influence of traffic load for wavelength conversion. The authors claimed that with respect to blocking probability, the benefit of wavelength conversion increasing with increasing traffic is only true up to a certain load level. The study further showed that with increasing traffic volume, the difference in blocking probability between networks with and without wavelength conversion is fairly constant. This difference does not increase with the increasing load. In addition, results also showed that the wavelength conversion gain actually decreases with increasing traffic volume above a certain load level. Unfortunately, these studies focused on the increase in traffic load, whereas the influence of fluctuation in traffic patterns is not considered.

To study the effects of wavelength conversion on traffic forecast tolerance, two sparse wavelength conversion schemes are compared under various traffic pattern scenarios, in particular, the sparse nodal conversion and sparse switch-output conversion schemes, as discussed in Section 5.1.1. The wavelength conversion placement schemes are termed localized placement and distributed placement respectively in this study. The first strategy makes use of full wavelength conversion in a limited number of nodes. The second strategy uses a limited number of wavelength converters in all the nodes. Comparison of the mean blocking probabilities and the standard deviations in the blocking probability in non-uniform loading for both cases is carried out to assess each strategy in improving the network traffic forecast tolerance.

Two network topologies were chosen, the real NSFNET network and an 8-node-ring network. The NSFNET was chosen because its medium size is representative of the majority of practical core networks, whereas the ring topology was chosen due to its simplicity for deployment and popularity in the SDH/SONET architecture. The optimal placement of wavelength conversion is set according to the findings in [Ine99] for NSFNET (An exhaustive search for the 'best' placement of nodes with full wavelength conversion was carried out, and ordered in descending order according to their improvement of the blocking performance). The nodes in NSFNET network equipped with full wavelength conversion are shown in Fig.5.4. In the case of the 8-node-ring network, the optimal wavelength conversion placement is set according to

the results published in [Ven99], so that the wavelength converters were placed as uniformly as possible for the ring network. The nodes with wavelength converters in the ring topology are shown in Fig.5.4. Full wavelength conversion is provided at two nodes, 4 links apart in the ring topology.

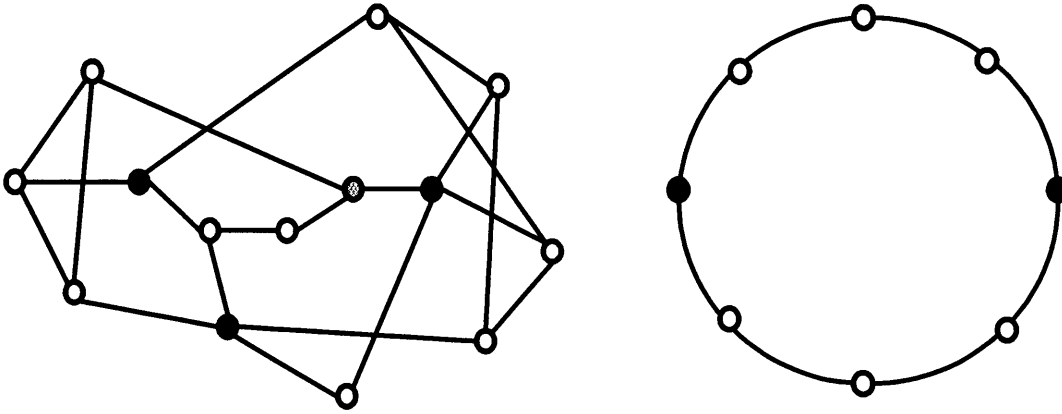


Figure 5.4 - NSFNET and 8-node-ring topologies with full wavelength conversion at some of the network nodes

The proposed dynamic operating scheme described in section 5.2.1 was employed for both networks to carry out comparisons of the two sparse wavelength conversion schemes. For each network node-pair, two alternate shortest paths were considered.

The NSFNET topology was initially considered for testing the two placement schemes with the same number of converters in each case. For the localized placement scheme, wavelength conversion was equipped on all channels in the two nodes shown in black in Fig.5.4, corresponding to the optimum placement given in [Ine99]. For the distributed scheme, two wavelength converters were provided for each outgoing fibre in every node. Twelve wavelengths per fibre were used, resulting in a total of 84 wavelength converters in the network in both schemes. Full wavelength-conversion range is assumed i.e. any input wavelength can be converted to any output wavelength. A total network load of 113.75 Erlangs was used in both schemes. Results are shown in Fig.5.5 of mean blocking probabilities and blocking probability standard deviation versus the traffic non-uniformity factor.

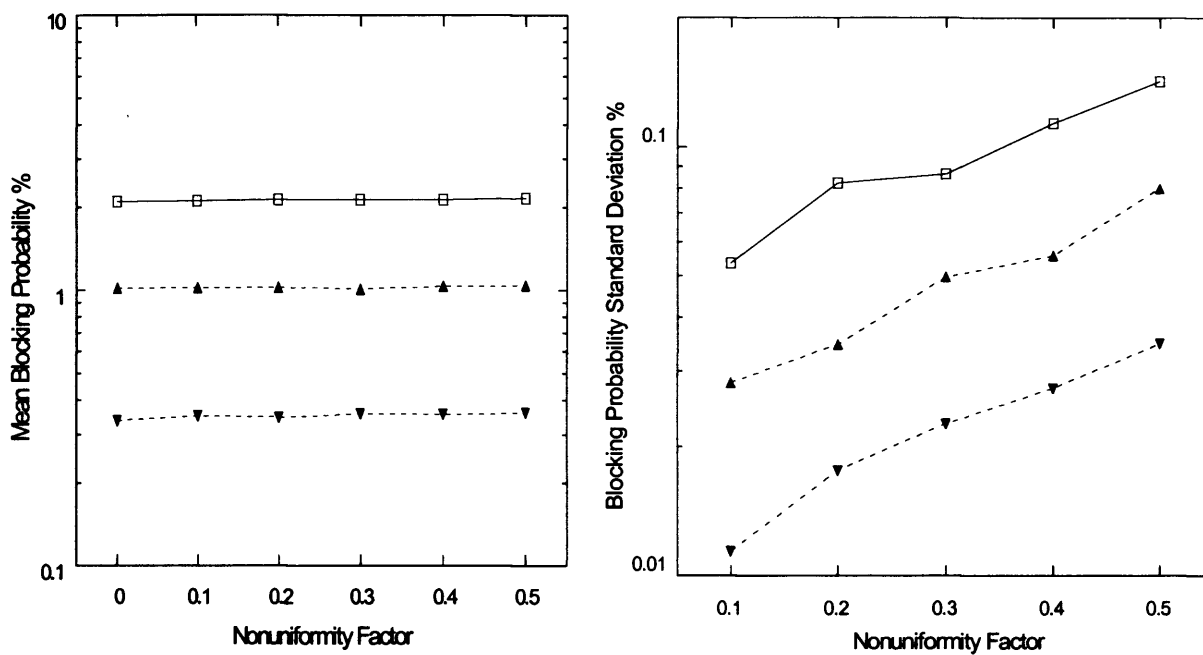


Figure 5.5 - Mean (left) and standard deviation (right) values of blocking probability without wavelength conversion (open squares), with localised (solid triangles), and distributed (solid inverted triangles) wavelength conversion placement schemes for the NSFNET network.

It can be seen that the distributed placement scheme results in better performance for all traffic pattern scenarios considered, with mean blocking probability nearly 3 times lower and standard deviation of blocking probability a factor of 2.3 lower (at a non-uniformity factor of 0.5) compared with those with the localised scheme.

Both schemes were also tested with the 8-node-ring topology, with 12 wavelengths per fibre, a network load of 35 Erlangs, and 48 wavelength converters. With the localised placement scheme, full wavelength conversion was provided at two nodes shown in black in Fig.5.4. In the case of the distributed placement, each outgoing fibre of every network node was equipped with three wavelength converters. The same trend was found as for the NSFNET topology, with the distributed placement scheme giving better performance as shown in Fig.5.6.

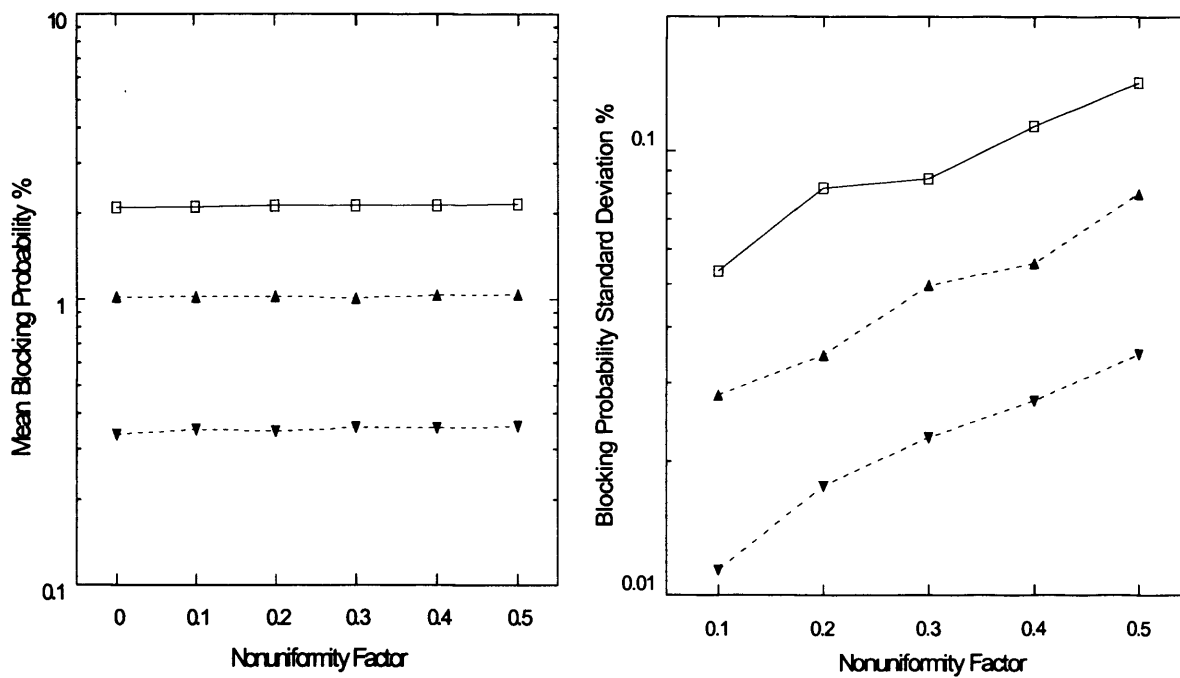


Figure 5.6 - Mean (left) and standard deviation (right) values of blocking probability without wavelength conversion (open squares), with localised (solid triangles), and distributed (solid inverted triangles) wavelength conversion placement schemes for the 8-node-ring network.

The traffic forecast tolerance achieved with the two schemes was then compared with the number of wavelength converters adjusted so that the same mean blocking probability were obtained with uniform loading. In this case, the number of converters used in the localised scheme is larger than that used in the distributed case. Figure 5.7 (left) shows the results for the NSFNET topology, with 12 wavelengths and a network load of 113.75 Erlangs as before. With the localised placement scheme, full wavelength conversion was provided in the four nodes shown in gray and black in Fig.5.4, chosen with the optimum placement given in [Ine99] with 169 wavelength converters used in total. In the case of the distributed placement scheme, all outgoing fibres of every network node were equipped with just a single wavelength converter, requiring a total of 42 wavelength converters. It can be observed that there is no significant difference between the values of blocking probability standard deviation with the two schemes, showing that both achieve the same network traffic forecast tolerance. Simulations of the 8-node-ring network with 110 and 16 wavelength

converters used for localised and distributed schemes respectively resulted in similar findings, as shown in Fig.5.7 (right).

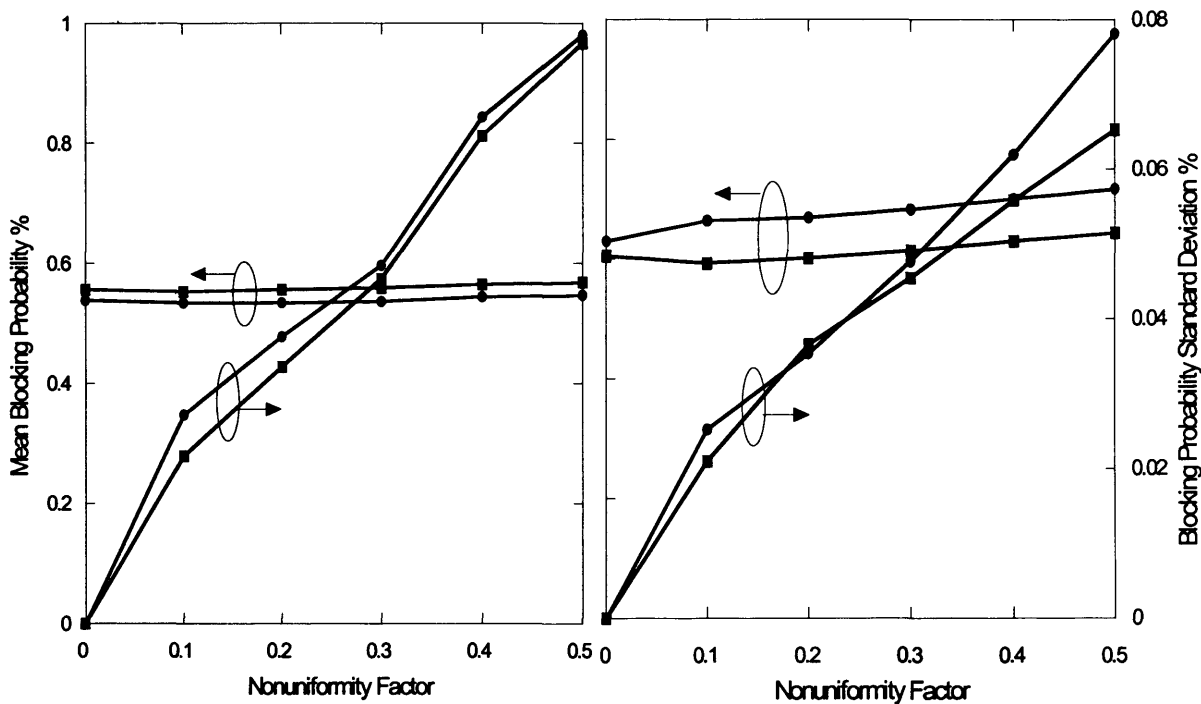


Figure 5.7 - Mean and standard deviation values of blocking probability with localised (circles) and distributed (squares) wavelength conversion placement schemes for the NSFNET (left) and 8-node-ring (right) topologies, with the number of wavelength converters chosen to obtain similar blocking probabilities with uniform traffic load.

In summary, two sparse wavelength conversion schemes were compared, with uniform and non-uniform dynamic traffic patterns. Both improved the network traffic forecast tolerance with respect to the cases in which wavelength conversion was not used. However, the results show that the distributed wavelength conversion scheme, in which every network node is provided with sparse wavelength conversion, significantly outperforms the localised placement scheme, in which a limited number of nodes are equipped with full wavelength conversion. With the same number of wavelength converters across the network, both the mean and the standard deviation of blocking probability were lower with the distributed placement scheme. However, equivalent network traffic forecast tolerance can be achieved with the two schemes, although at the expense of a larger number of wavelength converters with the localised placement scheme.



### 5.3 Summary

In this chapter, wavelength conversion is introduced to the dynamic wavelength-routed optical network model in order to enhance the network performance in terms of traffic forecast tolerance. Related studies of sparse wavelength conversion schemes, the optimal wavelength conversion placement, the RWA algorithms with wavelength conversion facility, and dynamic operating schemes in the case of wavelength conversions were discussed.

In addition, a novel operating scheme based on FAR-FF RWA algorithm is proposed. The aim of the scheme is to utilise the limited wavelength and wavelength conversion resources in a conservative manner so that the possibility for future lightpath establishment can be increased. Moreover, the proposed dynamic traffic model is employed to assess the effects of sparse wavelength conversion on traffic forecast tolerance. It is found that wavelength conversion can significantly increase the network capability to accommodate unpredictable traffic pattern variations. Besides the improvement through the application of wavelength conversion, it seems that the networks with higher mean overall blocking probability in the absence of wavelength conversion benefit most from wavelength conversion. Furthermore, two sparse wavelength conversion schemes, termed localised and distributed schemes respectively, were further compared with random traffic pattern variations. With the same number of wavelength converters used across the network, the distributed wavelength conversion scheme outperforms the localised wavelength conversion scheme, both in terms of the mean blocking probability and the standard deviation of blocking probability, and hence traffic forecast tolerance. However, with the number of wavelength converters in the localised scheme increased to obtain equivalent blocking in the uniform traffic case, the network's ability to handle traffic pattern fluctuations was found to be similar to that of the network with the distributed placement scheme.

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## Chapter 6 Summary and conclusions

The work described in this thesis focused on the study of the robustness of dynamic wavelength routed optical networks to unpredictable traffic pattern variations. Specifically, the studies carried out primarily concentrated on quantifying the network robustness, identifying the influences of network physical topological features on the network traffic forecast tolerance, and improving the network tolerance using wavelength conversion, using a variety of random traffic pattern scenarios. Such studies on the network robustness are key in designing, planning, and expanding dynamic optical networks. To the best of the author's knowledge, the work is the first comprehensive study of network traffic forecast tolerance to unpredictable traffic pattern variations.

A dynamic traffic distribution model was proposed to simulate the dynamic traffic environment, which not only describes some of the extreme traffic scenarios, but also generates both non-uniform and asymmetric traffic patterns. A technique was proposed to test various networks with the best-performing and worst-performing routing and wavelength allocation (RWA) algorithms, with various network topologies, and with different numbers of wavelengths under extreme traffic statistics. Furthermore, a metric was proposed to define the network robustness to the traffic pattern randomness, termed network traffic forecast tolerance, using the increase in the standard deviation of the blocking probability distribution with increasing traffic non-uniformity. The metric was integrated with a mathematical model to calculate the traffic forecast tolerance theoretically. In addition, the metric has been used to visually inspect results and infer traffic forecast tolerance. The results demonstrate that the traffic forecast tolerance can be quantified using the above metric. In addition, the network traffic forecast tolerance was found to be strongly influenced by the routing and wavelength allocation algorithm for any network topology, such that a better-performing RWA algorithm gives higher network tolerance. It was also shown that the traffic forecast tolerance is strongly related to the network topological layout, and indeed a small change in network physical link arrangements may lead to significant differences in the network tolerance. It was further found that networks

exhibiting lower overall blocking performance under uniform traffic tend to show higher traffic forecast tolerance.

The investigation of the physical features of the network topology on traffic forecast tolerance was carried out. In particular, two main network parameters, the average lightpath length and the wavelength requirement to fully interconnect all network nodes in static operation were studied, both with simulation and theory, for a variety of network topologies ranging from practical, deployed networks, such as NSFNET, to a large number of randomly connected networks. A strong correlation was found between the traffic forecast tolerance and both the average lightpath length and the wavelength requirement. The sensitivity to lightpath length was most evident for RWA algorithms which consider alternate paths in setting up each connection. The results of all these studies confirm the conclusion that networks with low overall blocking probability with uniform traffic generally exhibit high traffic forecast tolerance to unpredictable, varying traffic patterns.

To improve the network traffic forecast tolerance, wavelength conversion was studied. The results showed that wavelength conversion can significantly improve network traffic forecast tolerance. In addition, it was demonstrated that networks with sparse distributed wavelength conversion placement outperform sparse localised wavelength conversion placement (assuming the same number of wavelength converters across the network in each case) both in terms of minimising blocking probability with uniform traffic loading, and increasing network traffic forecast tolerance.

## Possible future work

Since this is one of the first studies of network robustness to traffic pattern variations, many areas can be expanded beyond the work described in this thesis. Specifically:

- The traffic model used in the thesis is based on Poisson traffic characteristics; however, due to the complex nature of traffic in the real world, the model can be further expanded using different traffic statistics.
- Since the average lightpath length and wavelength requirement in static operation have strong correlations with network traffic forecast tolerance, when designing or extending a network topology, these two findings can be used as a guidance to develop certain algorithm/mechanisms in an algorithm that automatically carries out the optimal physical link placement, ensuring maximum traffic forecast tolerance.
- Since sparse wavelength conversion schemes have been proven to significantly improve the traffic forecast tolerance, as lightpath physical lengths are reduced, a detailed investigation of sparse wavelength conversion and minimised lightpath length might lead to novel optimal wavelength conversion placement strategies.

## Appendix A

### Validation of the Simulation Results

This section presents the validation results using an analytical process, to confirm the simulation carried out in this work. Most results generated from this work are based on the discrete event simulation developed by the author using the Java programming language. Hence, it is important to validate the simulation results. However, as discussed in Section 3.4.1, it is very hard to obtain accurate theoretical results. Assumptions have to be made to simplify the mathematical model in order to give a reasonably accurate estimation.

Two models were utilised to assess the accuracy of the simulation, described in [Mok98Chapter3] [Kar98Chapter3] respectively. The model proposed in [Mok98Chapter3] can give good results for FAR-FF algorithms, whereas the model in [Kar98Chapter3] improves the previous model by characterising the overflow bursty traffic instead of assuming that it has Poisson statistics. However, the model in [Kar98Chapter3] can only give good results on well connected network topologies. The range of applicable network topologies is fairly small compared with the model proposed in [Mok98Chapter3]. In addition, the model in [Kar98Chapter3] only works with FR-FF algorithms. It is suggested that the model would give inaccurate results for FAR-FF algorithms. Hence, both models were employed to calculate the network blocking probability and compared with the simulation results.

The tested network topologies are a 6-node-ring network topology, EUROCORE network, ARPANET network, and randomly connected networks with 37 nodes and 47 links based on a range of physical connectivity of 0.4, 0.45, 0.16, and 0.0705 respectively. All the topologies can be found in Section 3.2.6. In addition, all networks are tested with uniform traffic and are equipped with 4 wavelengths per fibre since a large number of wavelengths causes inaccuracy with both analytical models. The traffic request arrivals are assumed as Poisson statistics with exponential

lightpath holding periods. The results of simulation, Mok98 model, and Kar98 Model are shown as below.

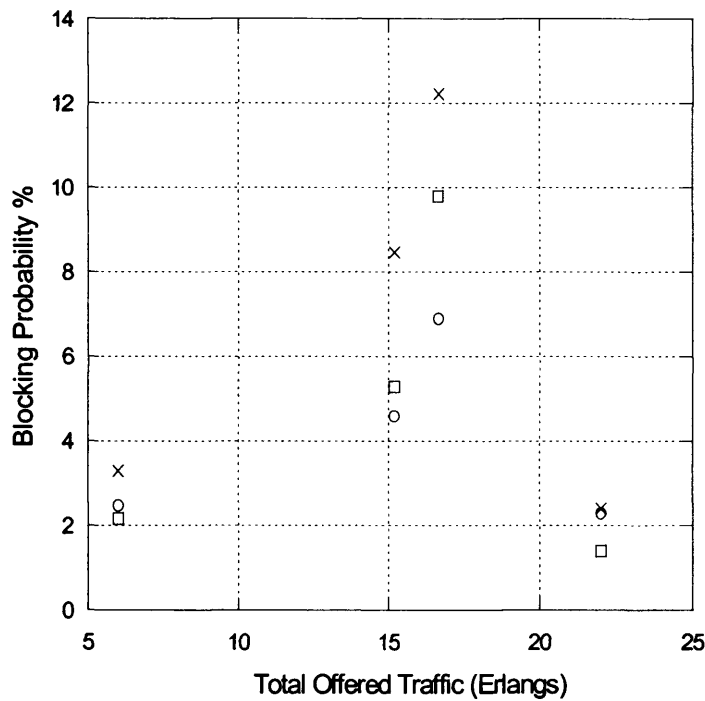


Figure A.1 - Total offered traffic load versus the overall blocking probability for network topologies. From left to right: 6-node-ring with 6 Erlangs; ARPANET with 15.2 Erlangs; RCN37N47L with 16.65 Erlangs; EUROCORE with 22 Erlangs.  
Circle: simulation result; square: Mok98 model result; Cross: Kar98 model result

It can be seen clearly that both the analytical models give quite accurate results compared with simulation. However, the discrepancies between Mok98 and Kar98 models are quite obvious for networks of ARPANET and RCN37N47L in that Mok98 model shows a better result than Kar98 model, since both networks have relatively smaller values of physical connectivity. The improvement given with the Kar98 model can be observed in results for the 6-node-ring and EUROCORE, in that the Kar98 model gives a closer result to the simulations than the Mok98 model. For any carefully chosen network topologies and with only a few wavelengths, both mathematical models can give good results compared with simulations. The reported results from this work were obtained with a degree of confidence of 95%. Moreover, since the Mok98 model can be employed for FAR-FF algorithm, whereas the Kar98 model is only applicable for FR-FF algorithm, the Mok98 model is further utilised and integrated with the theoretical study of traffic forecast tolerance in Section 3.4.2.

## Appendix B

# Routing and Wavelength Allocation in Static Wavelength-Routed Optical Networks: Heuristic Algorithm

This section presents a formal description of a heuristic algorithm utilised for the calculation of static case wavelength requirement in single-fibre static wavelength-routed optical networks without wavelength conversion.

Consider a network with  $N$  nodes and  $L$  links. Let  $G = G(N, A)$  be the network graph consisting of links,  $j \in A$ , with  $|A| = L$ , and nodes,  $N = \{1, 2, \dots, |N|\}$ , with  $|N| = N$ . A path  $p \subseteq A$  is a connected series of arcs, written as  $p: s(p) \rightarrow d(p)$ , from source node  $s(p)$  to destination node  $d(p)$  not including any cycles. Let  $l(p)$  be the length of the path as measured by the number of arcs. Define  $I(j \in p) = 1$  if  $j$  is an arc of path  $p$  and  $I(j \in p) = 0$  otherwise. The set of node-pairs is represented in the graph  $G(N, A)$  by

$$Z = \{(z_1, z_2) \in N \times N \mid z_1 < z_2\}$$

define  $\forall z = (z_1, z_2) \in Z$ ,  $MNH(z_1, z_2, G(N, A)) = m(z)$  to be the minimum number of hop (or physical links) distance between  $z_1$  and  $z_2$ , and for  $e = 0, 1, \dots$

$$A_{z,e} = \{p: z_1 \rightarrow z_2 \mid l(p) \leq MNH(z_1, z_2, G(N, A)) + e = m(z) + e\}$$

to be the set of paths connecting the node-pair  $z$  with length at most the minimum length  $m(z)$  plus constant  $e$ . By setting value of the constant  $e$  it is possible to control the size of set  $A_{z,e}$ .

### Phase I: setup

1. For each node-pair  $z = (z_1, z_2) \in Z$  determine a random list  $A_{z,e}$  of paths between  $z_1$  and  $z_2$  with length at most  $m(z) + e$ .

2. Determine a list  $P$  with all node-pairs  $z \in Z$  sorted by decreasing length of their MNH distance  $m(z)$ , with equal-length paths ordered randomly

### Phase II: initial path assignment

1. Set congestion  $c_j = 0, \forall j \in A$
2. Set  $\delta_{p,z}^A = 0, \forall p \in A_{z,e}, \forall z \in Z$
3. Select first  $z$  from  $P$
4. Set  $MAX_{LOAD} = \infty$  and  $PATH_{LOAD} = \infty$
5. Select first path  $p$  from  $A_{z,e}$
6. Determine  $M_{LOAD}$  as the maximum congestion among all the links in  $p$  ( $M_{LOAD} = \max_{j \in p} c_j$ ), and  $P_{LOAD}$  as the sum of the congestion of all links in  $p$  ( $P_{LOAD} = \sum_{j \in p} c_j$ )
7. If  $((M_{LOAD} < MAX_{LOAD})$  or  $((M_{LOAD} == MAX_{LOAD})$  and  $(P_{LOAD} < PATH_{LOAD})))$  , set  $p^* = p$  ,  $MAX_{LOAD} = M_{LOAD}$  , and  $PATH_{LOAD} = P_{LOAD}$
8. If there is a further path in  $A_{z,e}$  not yet considered select it as new  $p$  and go to step 6
9. Assign path  $p^*$  to node-pair  $z$  (set  $\delta_{p^*,z}^A = 1$ ), and increase the congestion of all the links in  $p^*$  ( $c_j = c_j + 1, \forall j \in p^*$ )
10. If there is a further node-pair in  $P$  not yet considered, select it as new  $z$  and go to step 4

### Phase III: subsequent optimisation

1. Set  $\delta_{p,z}^C = \delta_{p,z}^A, \forall p \in A_{z,e}, \forall z \in Z$
2. Calculate the list  $P$  of all node-pairs  $z$  sorted by decreasing length of their MNH distance  $m(z)$ , with ties broken randomly
3. Select first  $z$  from  $P$

4. Delete path  $p^*$  previously assigned to  $z$  (set  $\delta_{p^*,z}^A = 0$ ), and decrease the congestion along  $p^*$  ( $c_j = c_j - 1, \forall j \in p^*$ )
5. Repeat all the steps 4-9 of Phase II
6. If there is a further node-pair in  $P$  not yet considered, select it as new  $z$  and go to 4
7. If there exists at least one node-pair  $z \in Z$  and a path  $p \in A_{z,e}$  such that  $\delta_{p,z}^C \neq \delta_{p,z}^A$ , go to step 1

#### Phase IV: wavelength allocation

1. Determine a list  $P$  of all node-pairs  $z$  sorted by decreasing length of their assigned paths  $p^*$ , with equal-length paths ordered randomly
2. Set the list of wavelengths used in each link to be the empty set ( $\Lambda_j = \emptyset, \forall j \in A$ )
3. Select first  $z$  from  $P$
4. Consider the path  $p^*$  assigned to  $z$
5. Determine  $w^*$  as the lowest wavelength not used among all the links in  $p^*$ . Assign  $w^*$  to  $z$  (set  $\delta_{p^*,w^*,z}^A = 1$ ), and add  $w^*$  to the set of used wavelengths in all links in  $p^*$  ( $\Lambda_j = \Lambda_j \cup \{w^*\}, \forall j \in p^*$ )
6. If there is a further node-pair in  $P$  not yet considered, select it as new  $z$  and go to 4
7.  $N_\lambda = \left| \bigcup_{j \in A} \Lambda_j \right|$

In Phase II, each node-pair  $z$  is assigned the lowest cost path according to the values of the link congestion  $c_j$  when  $z$  is considered. Therefore, different solutions are obtained for different ordered lists  $P$ . To achieve the best possible allocation of the paths, independently of the order in list  $P$ , Phase III is performed. Each node-pair is considered at a time, and the path  $p^*$  previously assigned is replaced by a different one if, and only if, the maximum congestion along the new path is smaller than the maximum congestion in the path previously assigned. Phase III is repeated until no



improvements are possible. In Phase IV, the wavelengths are then assigned to the paths, ranked by decreasing length. The total number of distinct wavelengths assigned amongst all node-pairs determines the network wavelength requirement  $N_\lambda$ .

## Appendix C

### K Shortest Path Routing: Calculating the Average Lightpath Length and Deriving the Upper Bound

This section presents a formal description for the calculation of average lightpath length based on  $k$  shortest path routing in wavelength-routed optical networks. An upper bound for the average lightpath length can be obtained as well.

Consider  $K$  shortest paths for each node-pair  $z$ . These  $K$  shortest paths are assumed to be link-disjoint, in other words, no two shortest paths for the same node-pair,  $z$ , share the same physical link. It should be noted that the real number of disjoint paths that can be found for each node-pair equals the minimum nodal degree of the source node,  $z_s$ , and the destination node,  $z_d$ . All parameters are consistent with those in Appendix A.

#### Phase I: setup

1. Determine a list  $P$  with all node-pairs  $\forall z \in Z$
2. Set total number of paths in the network,  $Q$ , as  $Q=0$

#### Phase II: finding shortest path

1. If there is still a node-pair  $z$  in list  $P$ , choose this node-pair  $z$  and restore network topology, let  $G = G(N, A)$  again
2. Set the number of shortest paths investigated for this node-pair,  $k_z$ , as  $k_z = 0$
3. Set the total path length for the node-pair,  $L_z$ , as  $L_z = 0$
4. Check if  $k_z = K$ , delete  $z$  from  $P$  and go to step 1
5. If it can find a minimum number of hop distance for node-pair  $z$ , as  $m(z)$ , update  $L_z = L_z + m(z)$ ,  $Q = Q + 1$ , and  $k_z = k_z + 1$ , otherwise, delete  $z$  from  $P$  and go to step 1
6. Generate new network topology,  $G = G'(N, A')$  so that  $A' \subset A$ , but  $\forall j \in m(z)$  path  $\notin A'$  and go to step 4

### Phase III: calculating average lightpath length

1. Calculate average lightpath length for network  $G$ ,  $L = \frac{\sum_{z \in Z} L_z}{Q}$

The upper bound on the average lightpath length can be obtained without setting the  $K$  limitation, hence all the paths for each node-pair can be found regardless of the path distance. In this case, step 2 and step 4 in Phase II can be ignored.

In Phase II, each time a shortest path has been found for a node-pair, all the links along the path will be deleted from the network topology. Based on this new topology, another shortest path is searched for, for this node-pair. The algorithm itself is a recursive process, which exhausts all the physical links between the source and destination nodes until no other shortest path can be found for the node-pair. In the case of a failure to find a shortest path, there is literally no physical links connecting the two nodes in the network.